Physics in Collision 2019

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Hard Probes in Heavy-Ion Collisions

from RHIC to LHC

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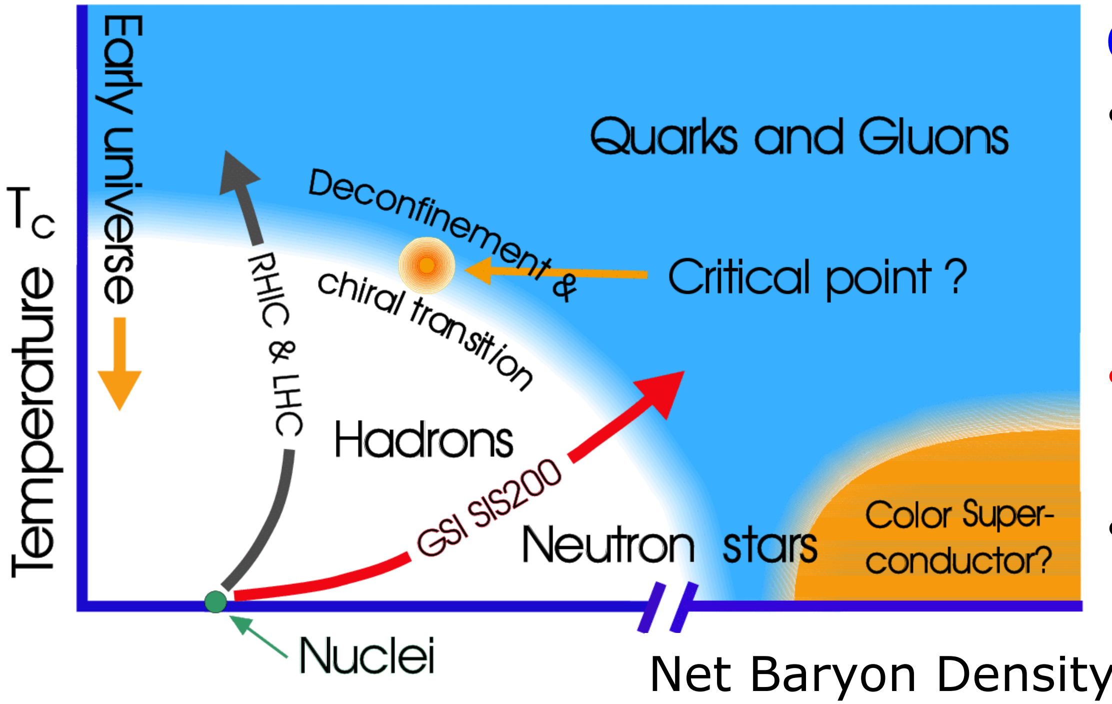
Outline

- Introduction
- Recent results on Jets
- Recent results on quarkonia
- Summary & Outlook

Quark gluon plasma (QGP)



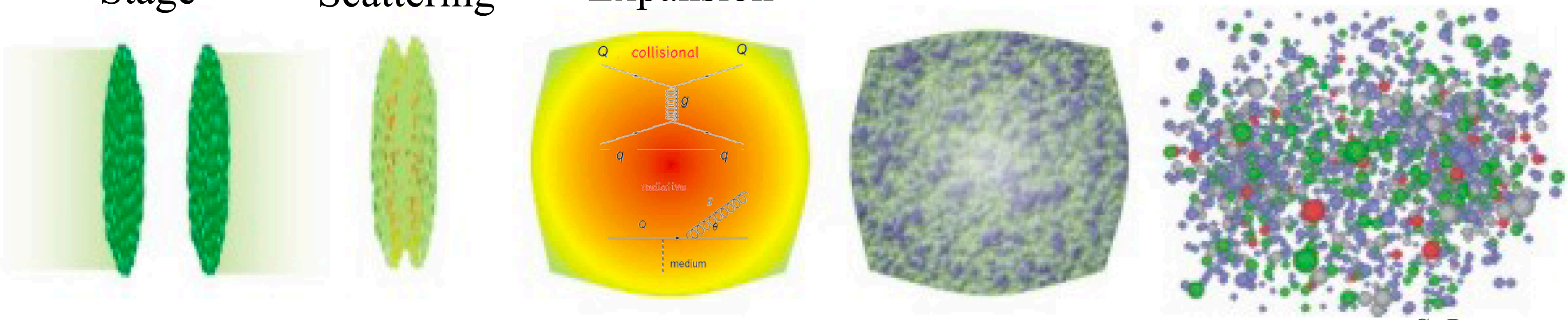
Quark gluon plasma (QGP):

- Many-body system with partonic degree of freedom
- Emergent properties
- The Universe was in this form ~μs after Big Bang

- Lattice QCD predicts phase transition at high temperature/density
- It was proposed to search for and study the properties of QGP via collisions of heavy ions at high energy
- Operating accelerators: RHIC@BNL, LHC@CERN…

Hard Probes: Penetrating probes of QGP

Initial Stage | Hard Scattering | QGP and Expansion | Hadronization | Hadronic phase



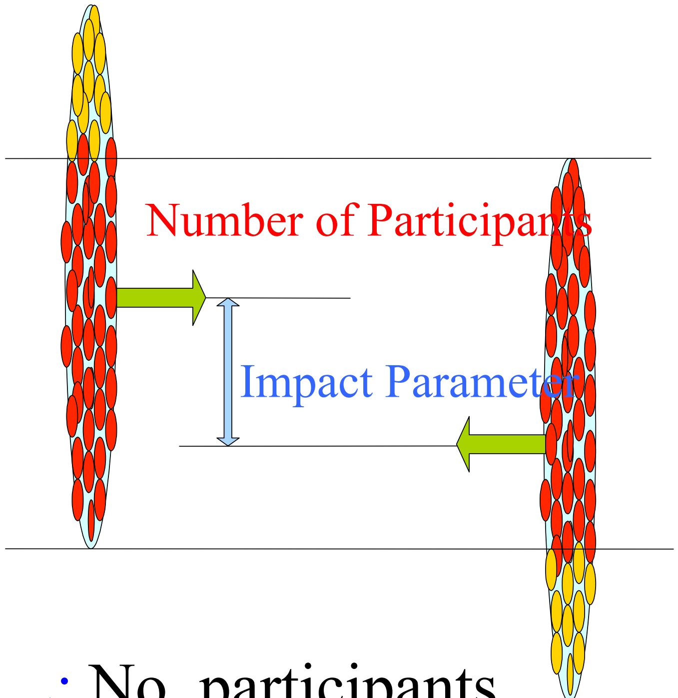
S. Bass

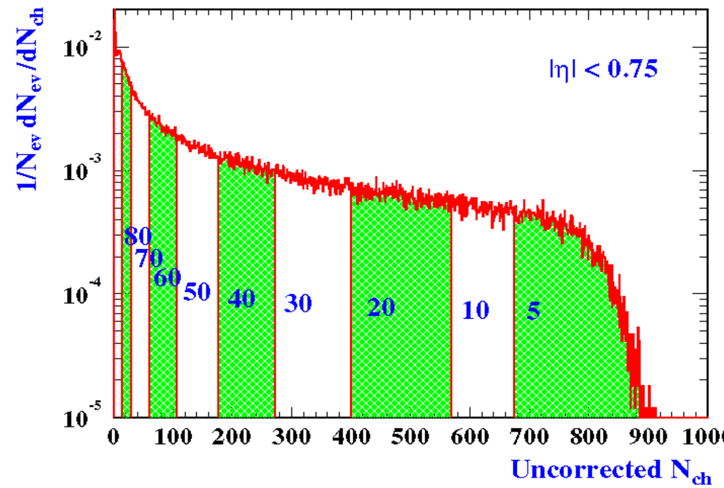
Hard Probes:

- Dominantly produced in the initial hard scatterings (before QGP formation)
  - Jets
  - Quarkonia

- Interact with the medium when penetrate the medium, probe QGP properties

Collisions geometry





N_{part}: No. participants

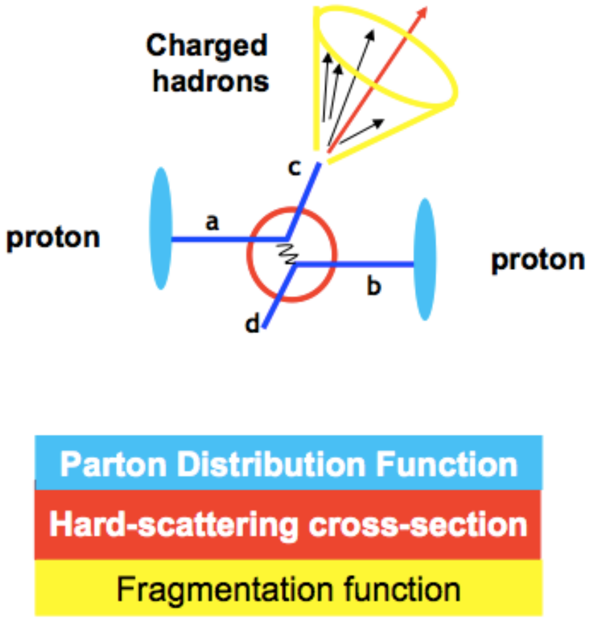
N_{coll}: No. binary nucleon-nucleon collisions

Central collisions:

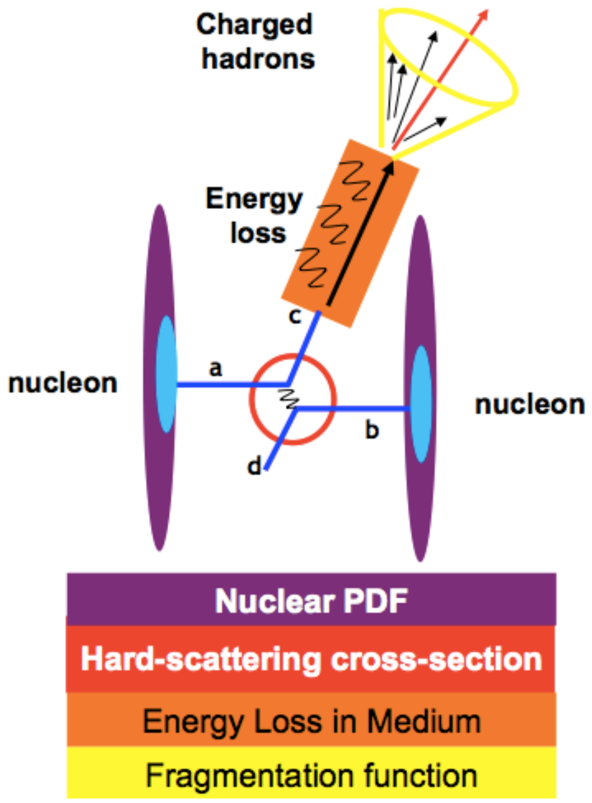
- Small impact parameter
- Large N_{part} and N_{coll}
- Large multiplicity

Centrality determined according to the measured (charged) multiplicity

Jets

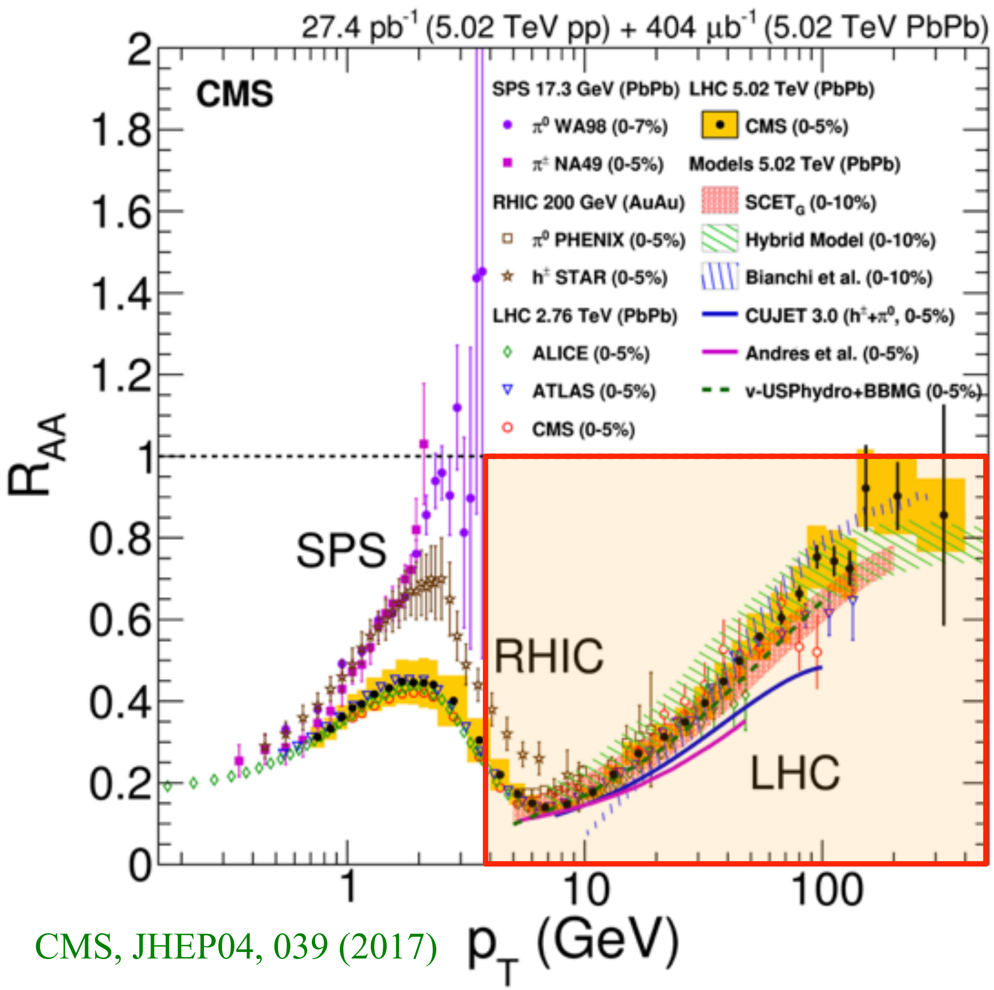


p+p collisions



Heavy-ion collisions

Suppression of high-p_T hadrons in A+A

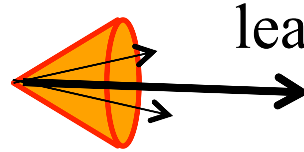


CMS, JHEP04, 039 (2017)

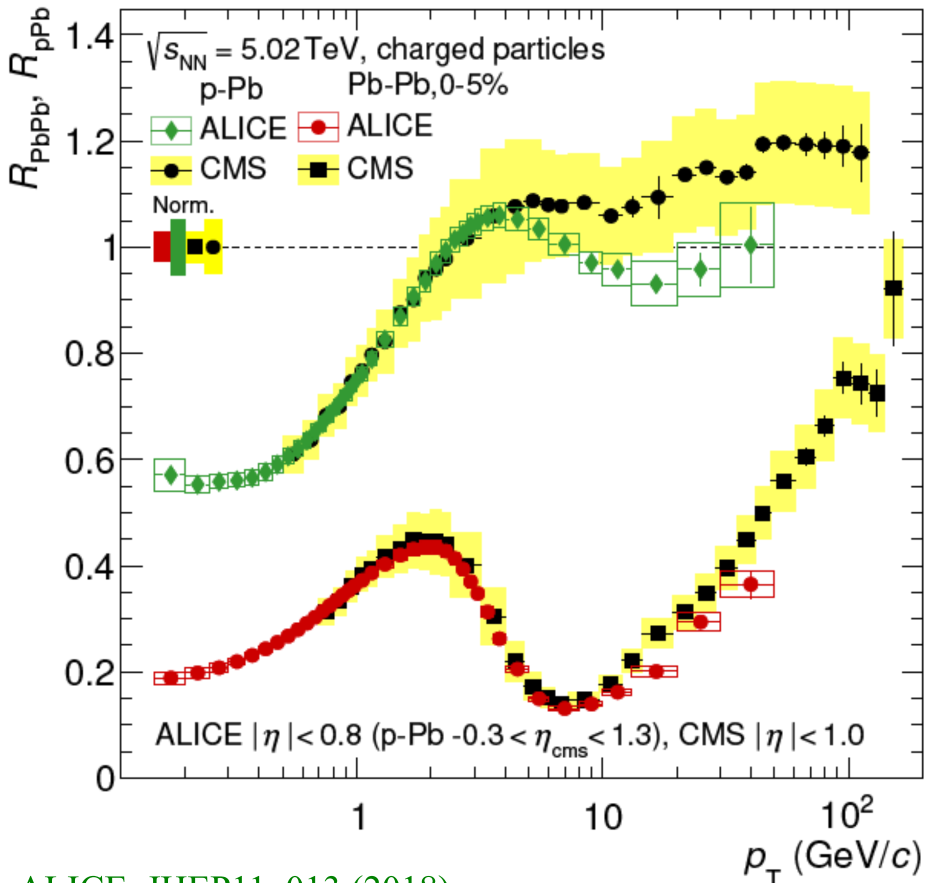
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

R_{AA}=1 if no medium effect

Significant suppression of high-p_T hadrons discovered at RHIC and confirmed at LHC with larger dynamic range



No suppression in p+Pb

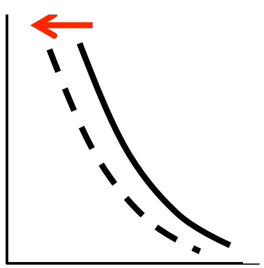


ALICE, JHEP11, 013 (2018)
CMS, JHEP04, 039 (2017)

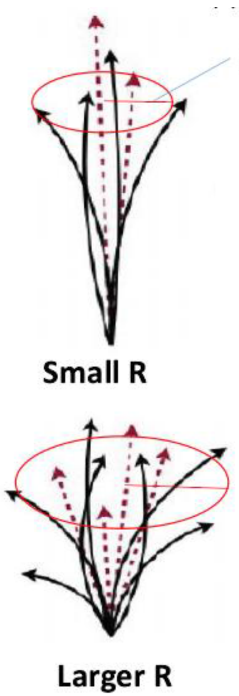
No suppression of mid/high-p_T hadrons in p+Pb

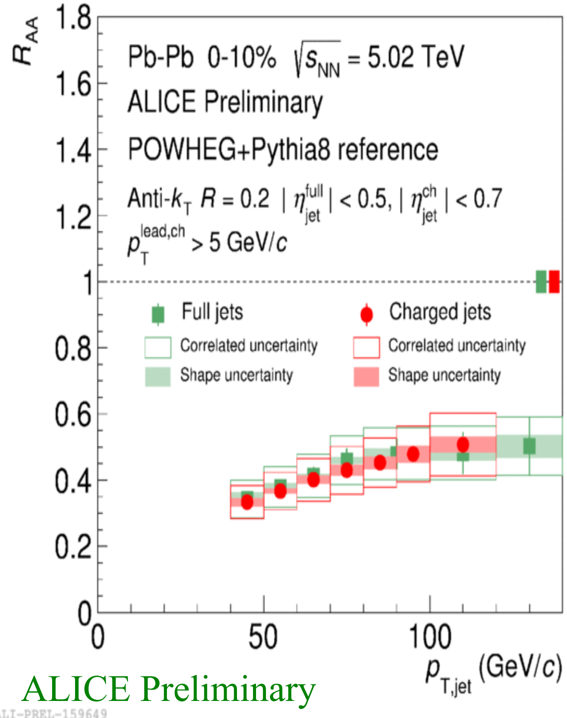
- The Run2 results confirmed results already achieved in Run1 at LHC

Suppression in heavy-ion collisions is due to final-state effects

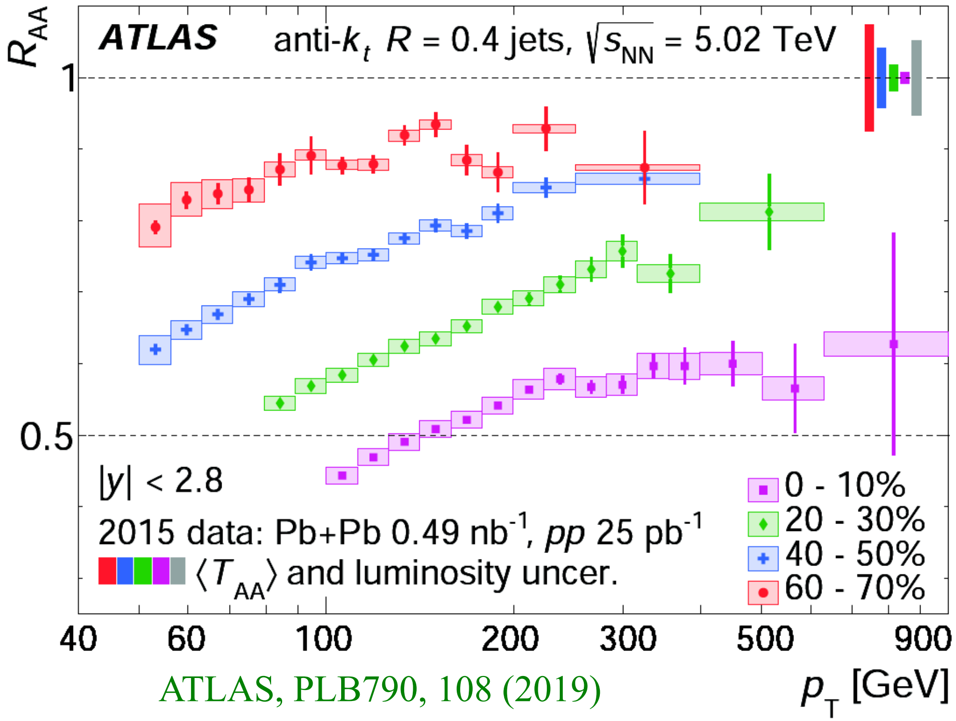


Recent results about suppression of jets





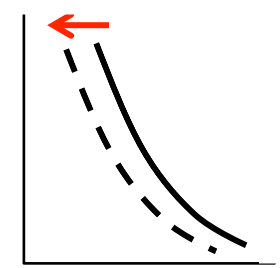
ALICE Preliminary



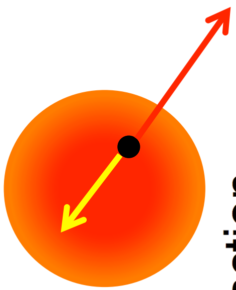
ATLAS, PLB790, 108 (2019)

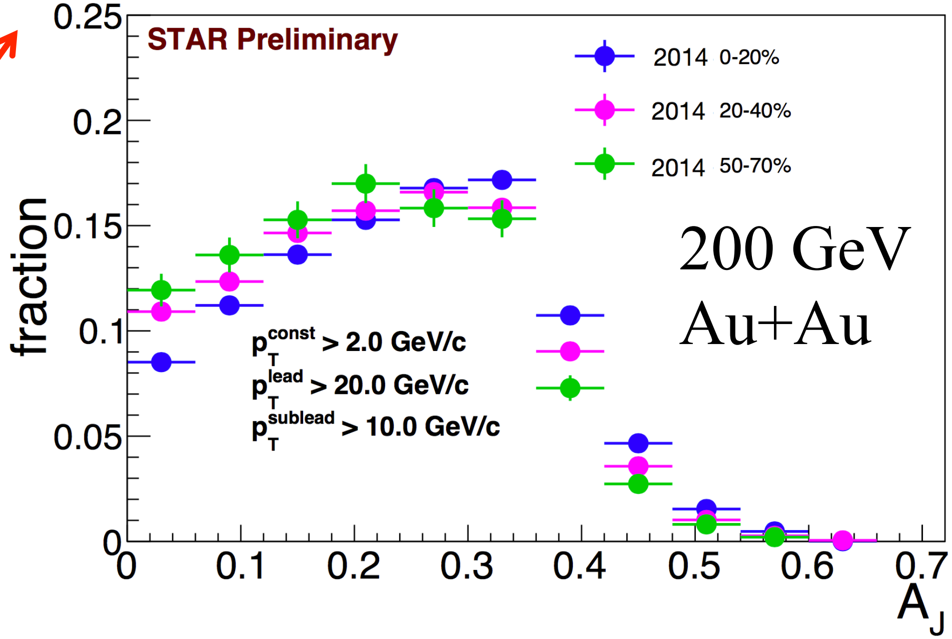
- Significant suppression of "fully" reconstructed jet is also observed from 40 GeV upto 900 GeV
- More suppression towards central collisions

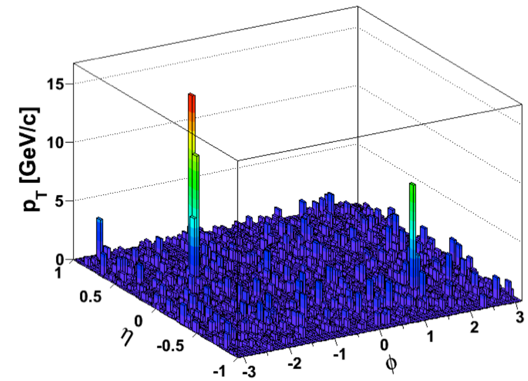
Shift of p_T spectrum due to energy loss



Di-jet imbalance





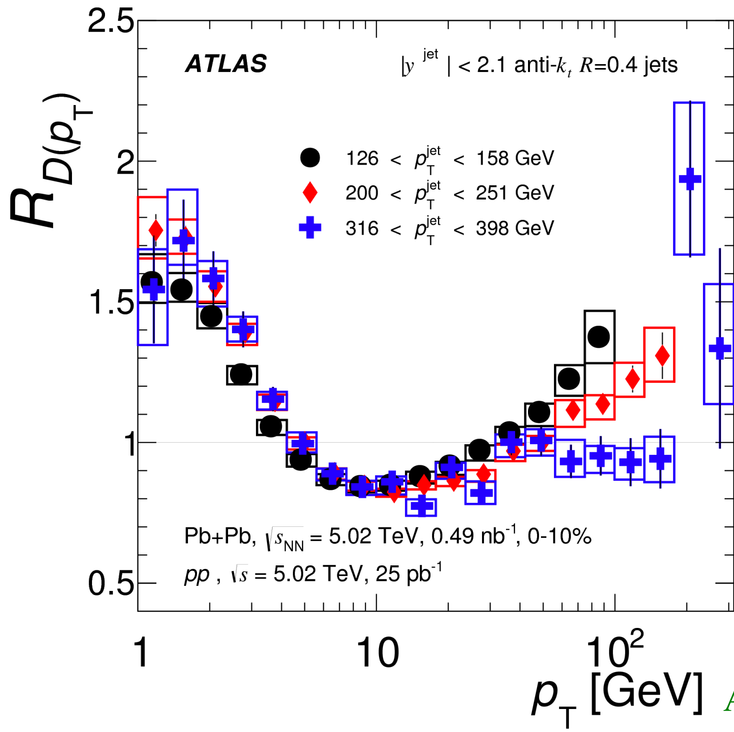


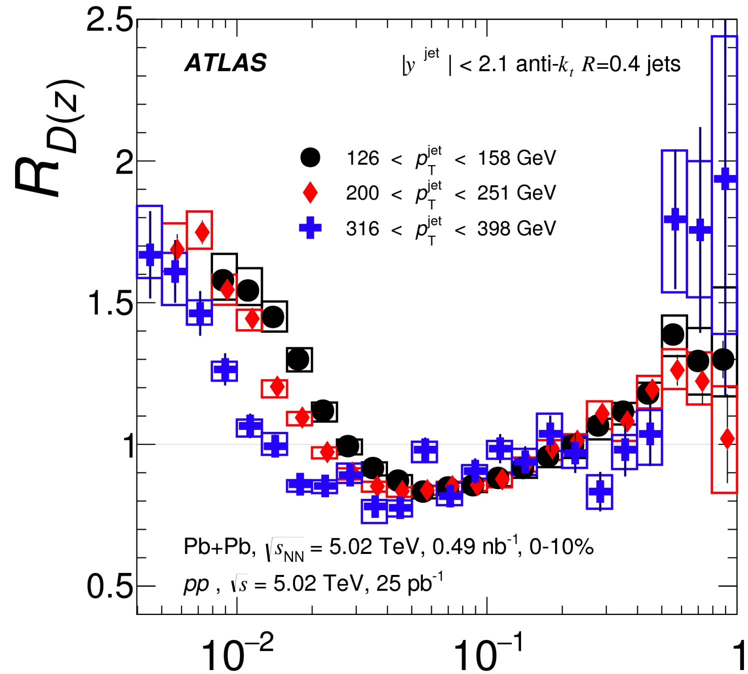
$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$

- Clear imbalance of di-jet observed in heavy-ion collisions
- More balanced in peripheral collisions than in central collisions

More results from jet geometry engineering are not shown

Modification of jet fragmentation





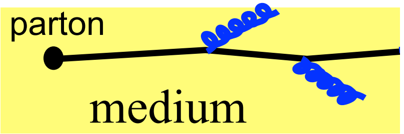
ATLAS, PLB790, 108 (2019)

$$R_{D(z)} = \frac{D(z)|_{\text{cent}}}{D(z)|_{pp}}$$

$$D(z) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}z}$$

$$z = \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{jet}} \cos \Delta R$$

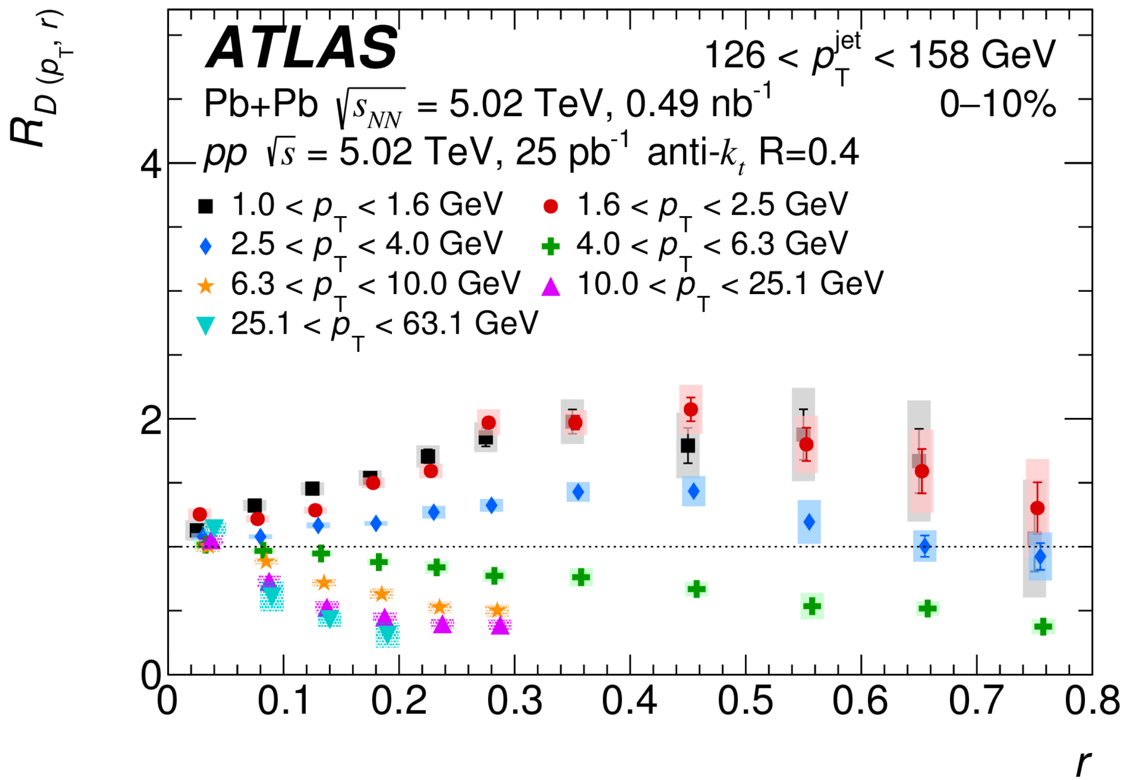
- Suppression at intermediate p_T or z
- Enhancement at low p_T or z



Hard parton interact with the medium and lose energy in the partonic phase (before fragmentation)

Modification of jet shape

ATLAS, arXiv:1908.05264

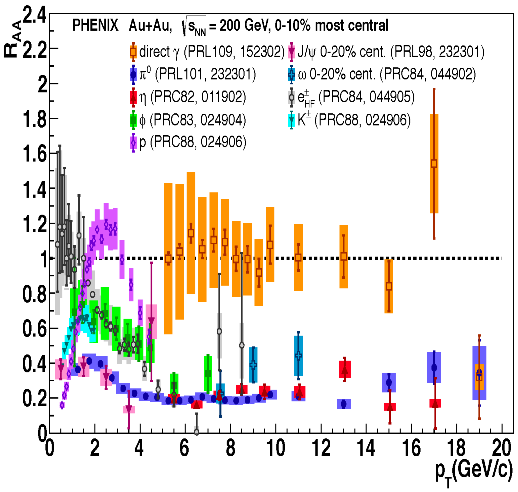


p_T< 4 GeV/c: Enhancement and increasing trend

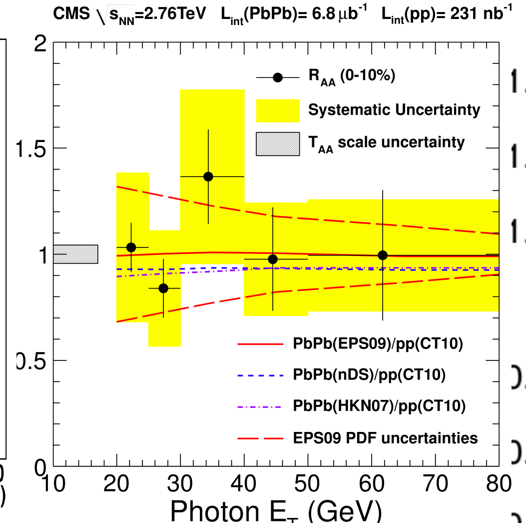
p_T>4 GeV/c: Suppression and decreasing trend

Lost energy transferred to low-p_T particles at large radial distance

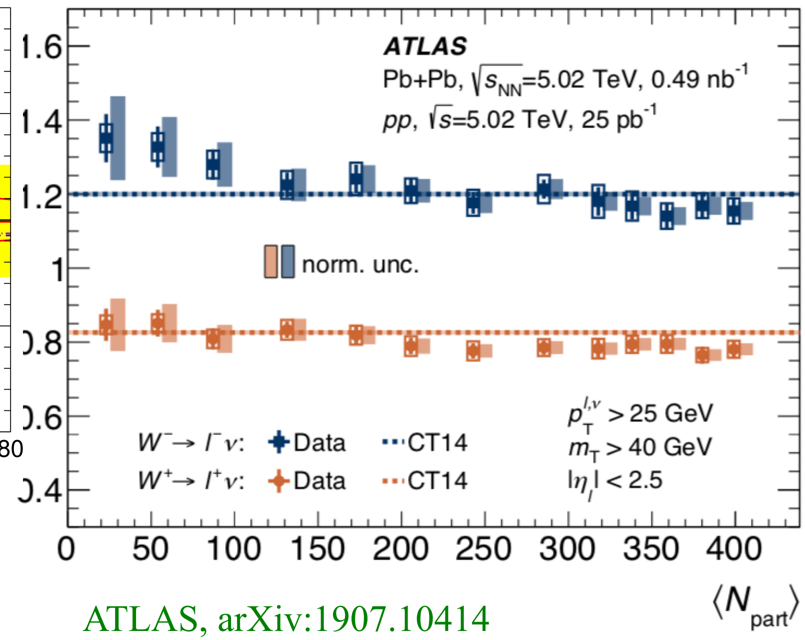
Bosons in heavy-ion collisions



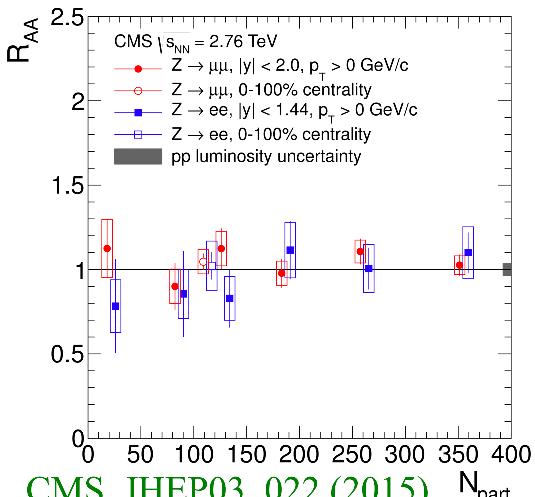
PHENIX, PRL109, 152302 (2012)



CMS, PLB710, 256 (2012)



ATLAS, arXiv:1907.10414



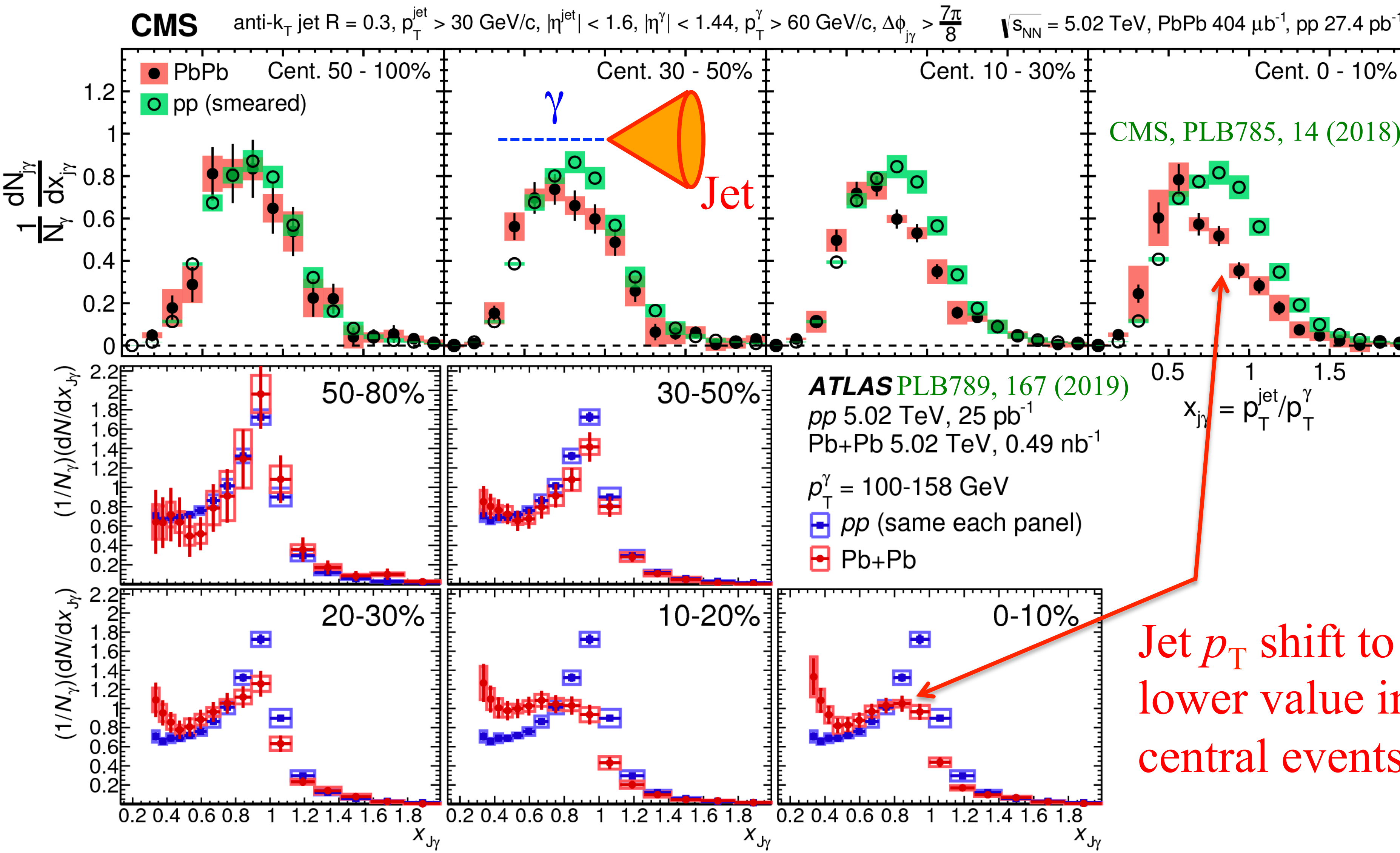
CMS, JHEP03, 022 (2015)

No suppression for isolated-photon, Z boson and W bosons in Pb+Pb collisions

Use them to define the initial kinematics

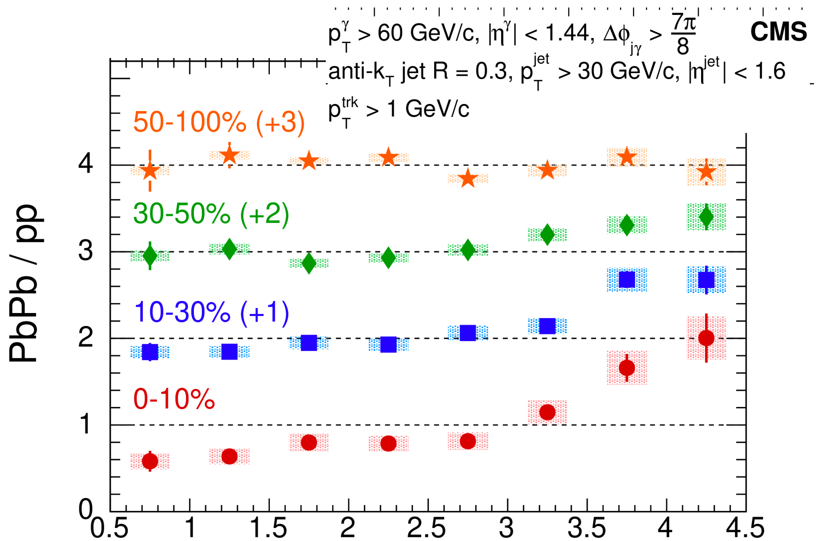
Isolated-photon and Z is preferred

Imbalance with isolated-photon

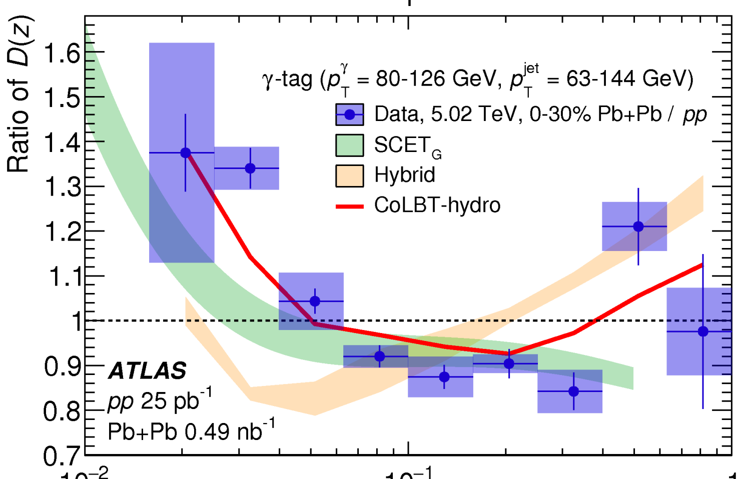


Jet p_T shift to lower value in central events

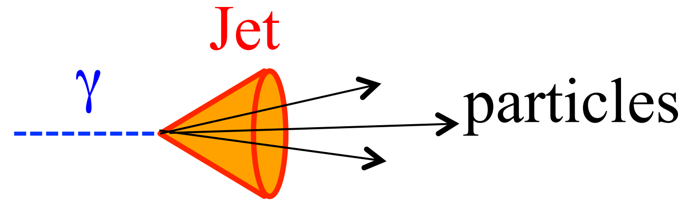
Jet fragmentation with isolated-photon



CMS, PRL121, 242301 (2018)



ATLAS, PRL123, 042001 (2019)



Well defined initial kinematics

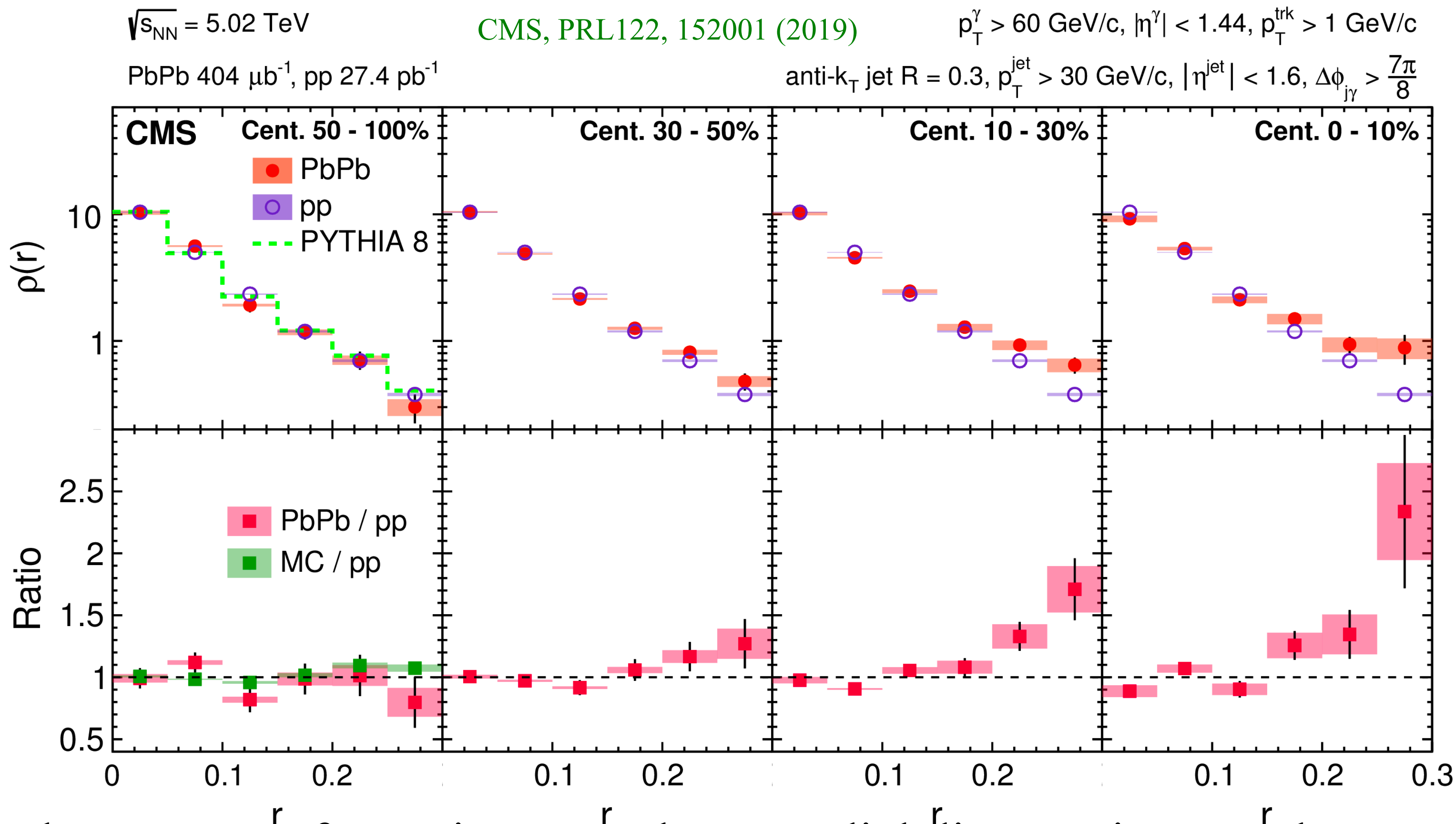
$$\xi_T^\gamma = ln\frac{-|\vec{p}_T^{\,\gamma}|^2}{\vec{p}_T^{\,trk}\cdot\vec{p}_T^{\,\gamma}} \qquad z = \frac{p_T}{p_T^{jet}}\cos\Delta R$$

50-100%: Consistent with p+p

0-30%:

- Enhancement for low-p_T tracks
- Suppression for intermediate-p_T tracks

Jet shape with isolated-photon

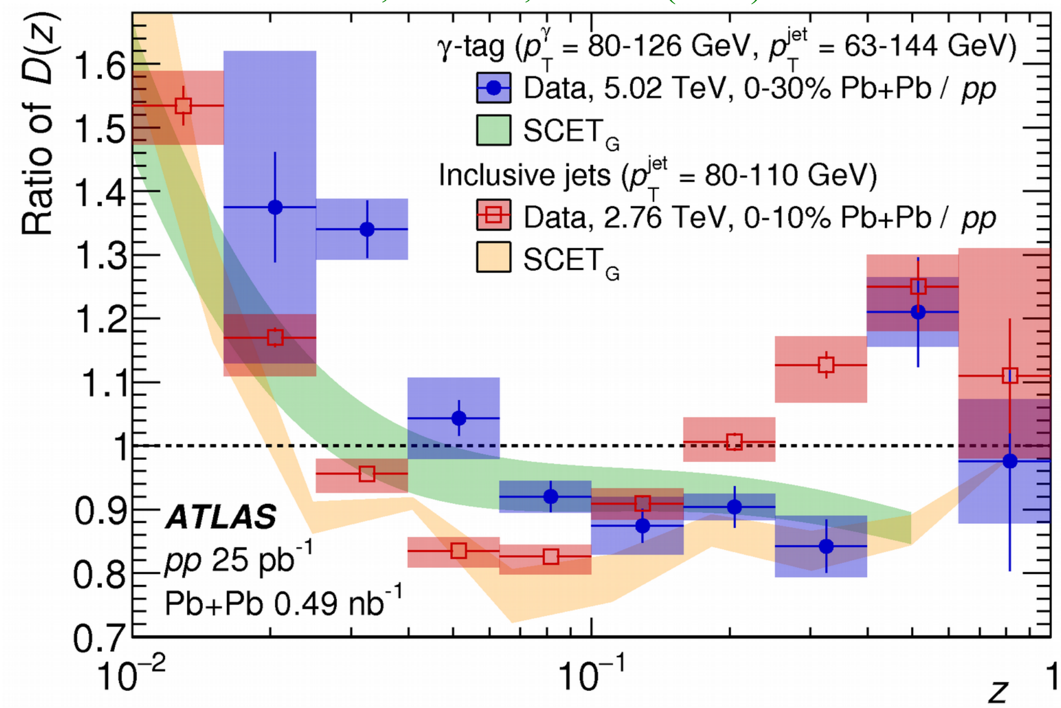


Enhancement of constituents at larger radial distance in central events

Direct observation of jet broadening in the QGP

Flavor dependent modification?

ATLAS, PRL123, 042001 (2019)



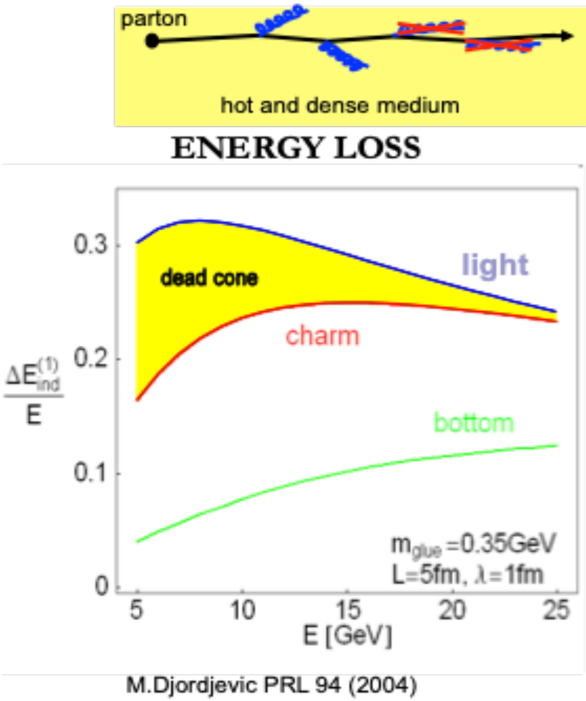
Note: kinematics are also different for two sets of jets

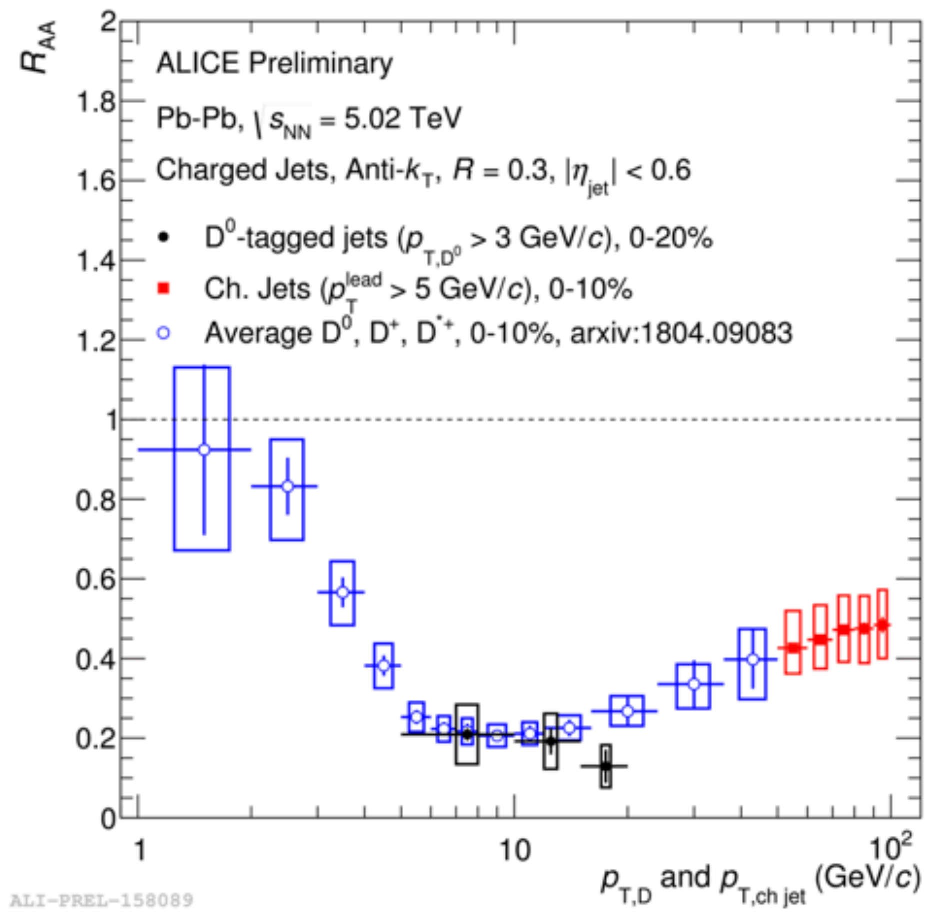
γ-tagged jet: quark jet dominant

Inclusive jet: gluon jet dominant

Fragmentation function W.R.T p+p shift to higher z for γ-tagged jet compared to inclusive jet → Color charge at play?

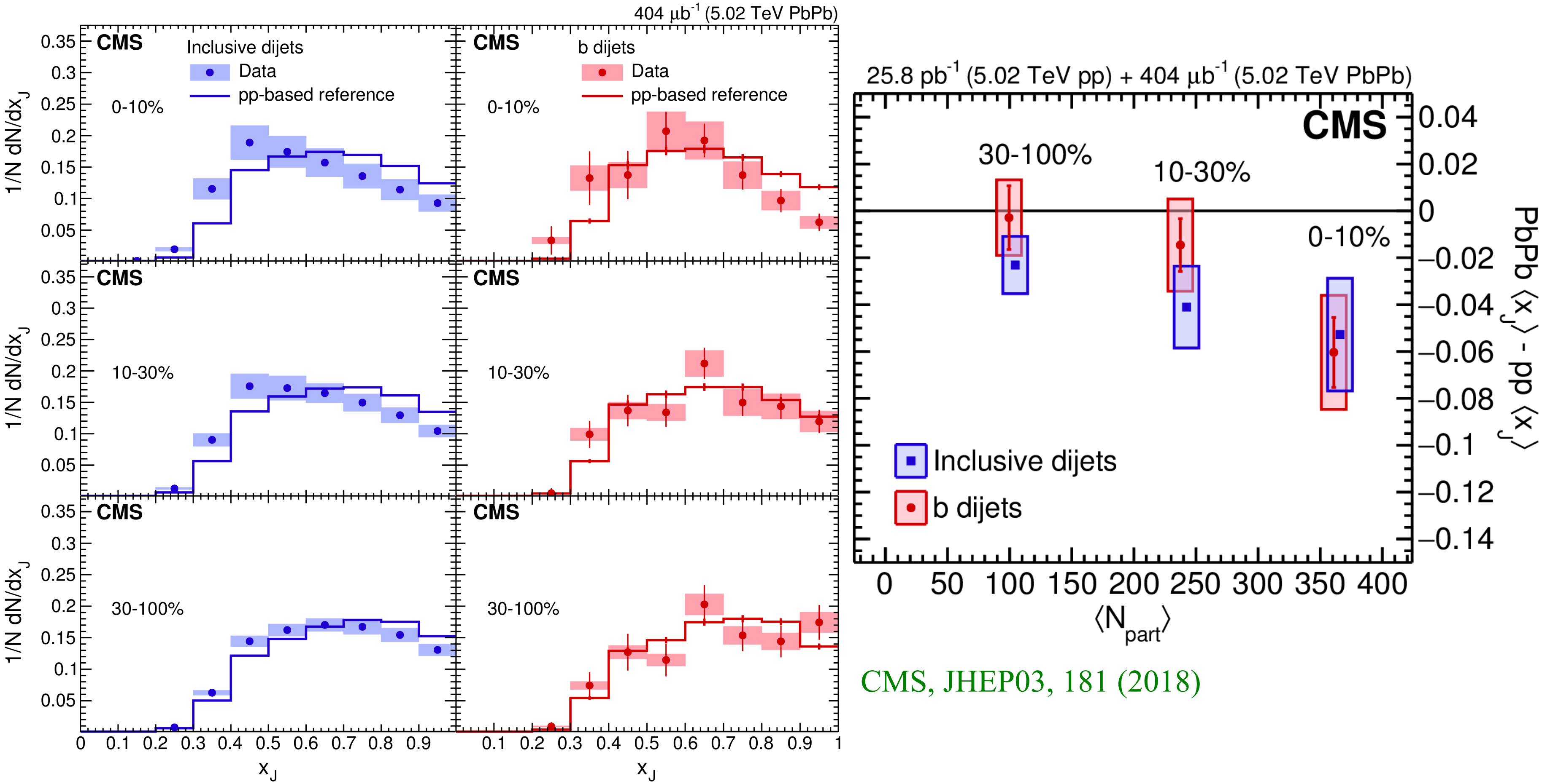
Suppression of charm jets





Similar suppression trend for D^0-tagged jets as for inclusive jets and D^0

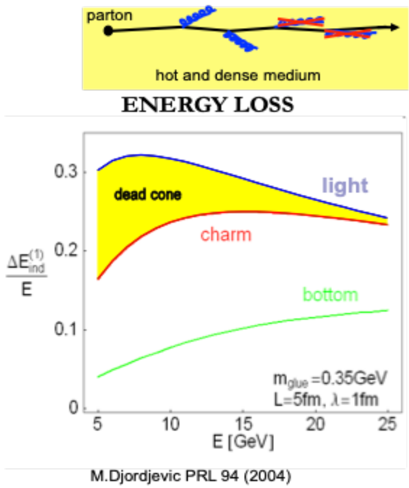
Imbalance of bottom jet pairs

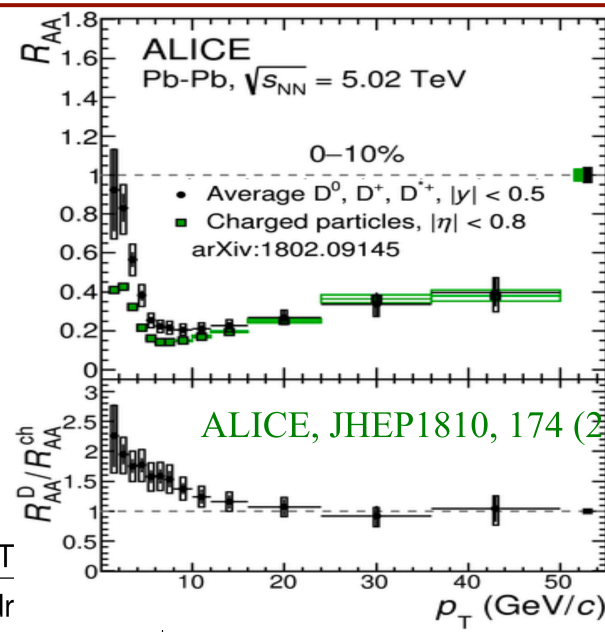


CMS, JHEP03, 181 (2018)

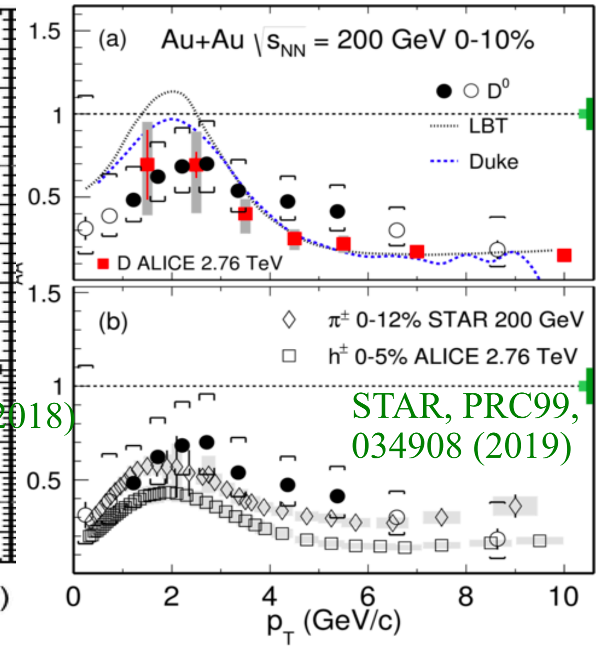
Similar imbalance for bottom di-jets as for inclusive di-jets

Flavor/mass dependent energy loss?

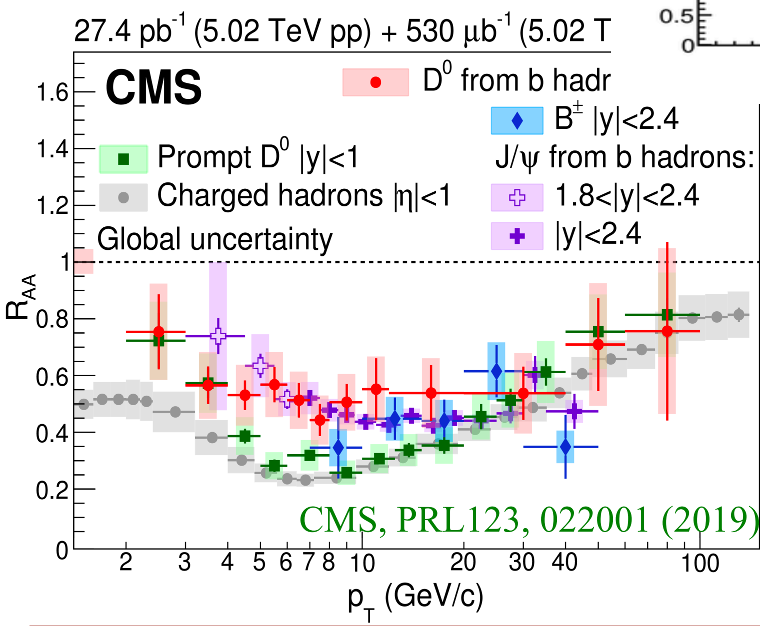




ALICE, JHEP1810, 174 (2018)



STAR, PRC99, 034908 (2019)



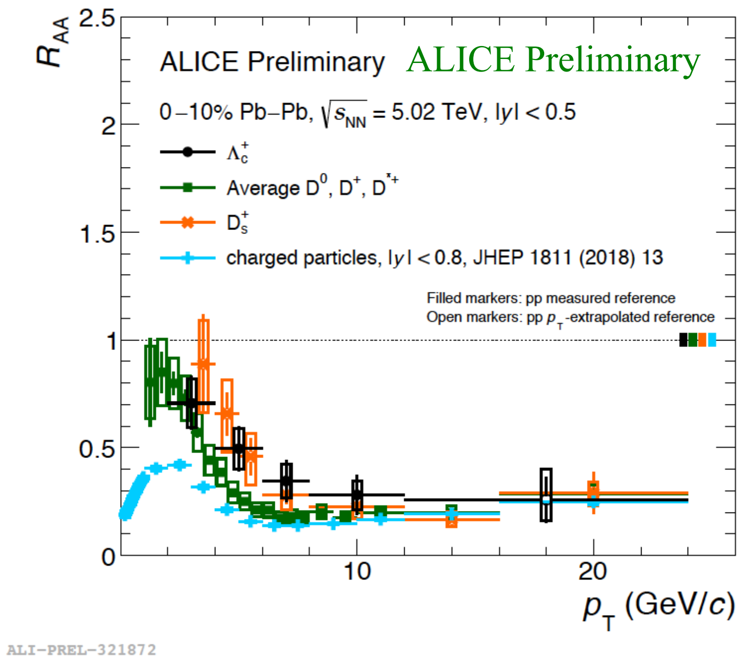
CMS, PRL123, 022001 (2019)

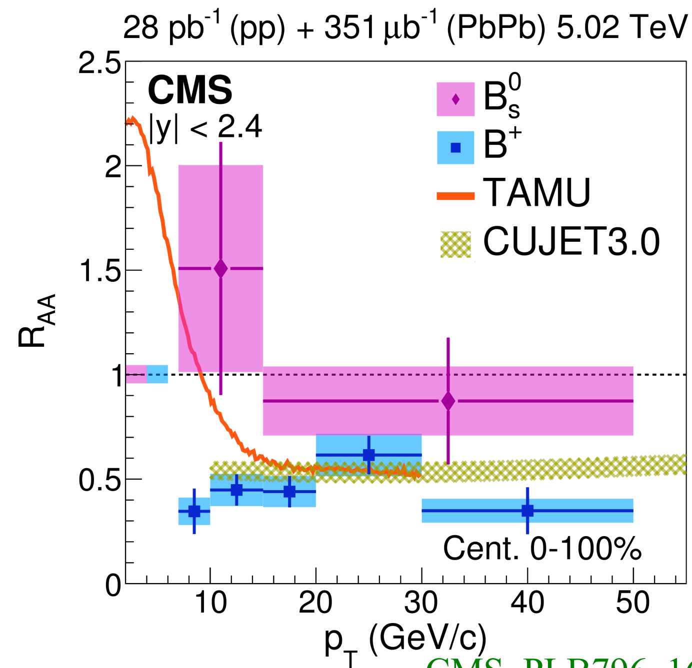
D > $h^{\pm}$ at intermediate but similar at high p_T

B-hadrons > prompt D at p_T<10 GeV/c but similar at high p_T

→ Observed mass dependence is in line with the expected dead cone effect

Heavy flavor hadron production





CMS, PLB796, 168 (2019)

- $R_{AA}(\Lambda_c^+)$ >~$R_{AA}(D_s^+)$ >$R_{AA}(D)$ > $R_{AA}(\pi)$ @ p_T<10 GeV/c @LHC
- Similar behavior observed @RHIC *(not shown)*

- $R_{AA}(B_s)$ > $R_{AA}(B^+)$ @ p_T<~20 GeV/c

Stay tuned!!

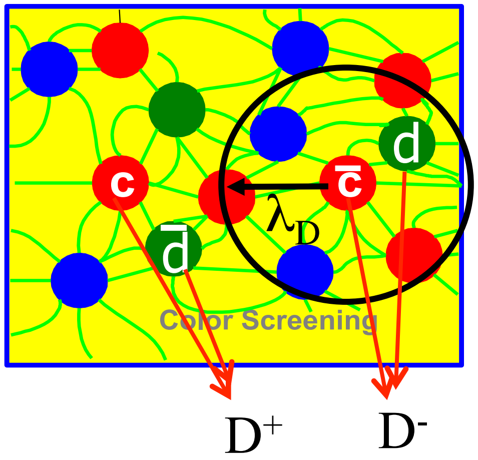
Hadronization mechanism is important at this region

Heavy quark transport in QGP + quark coalescece + (strangeness enhancement)?

Quarkonium suppression in QGP

In vacuum

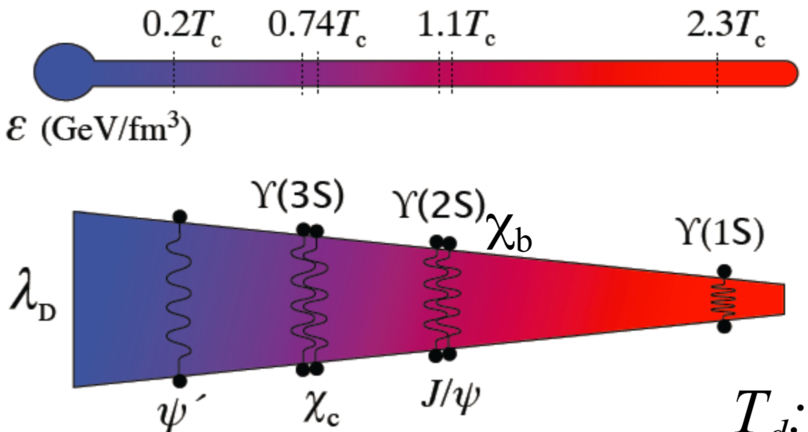
In QCD medium



$$\lambda_D \propto \frac{1}{T}$$

Dissociation in QGP due to color-screening

➔ ***Signature of QGP formation*** *T. Matsui, H. Sazt, PLB174, 416 (1986)*



T_d depends on quarkonium size

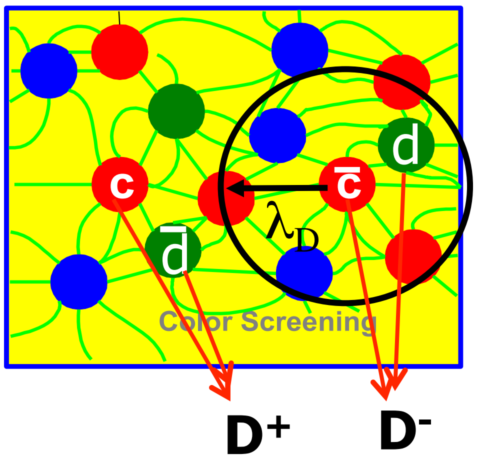
➔ ***Sequential melting***

➔ QGP Thermometer

T_d: dissociation temperature

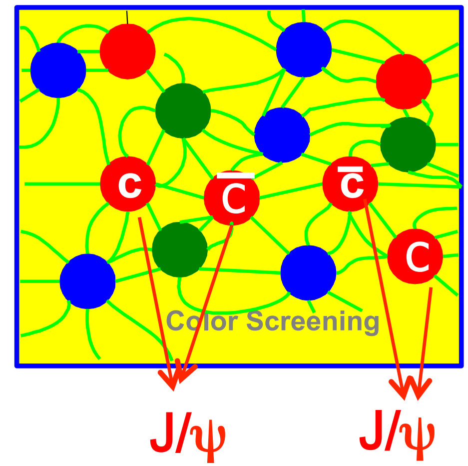
Quarkonium regeneration in QGP

Melting in QGP



vs.

Regeneration in QGP

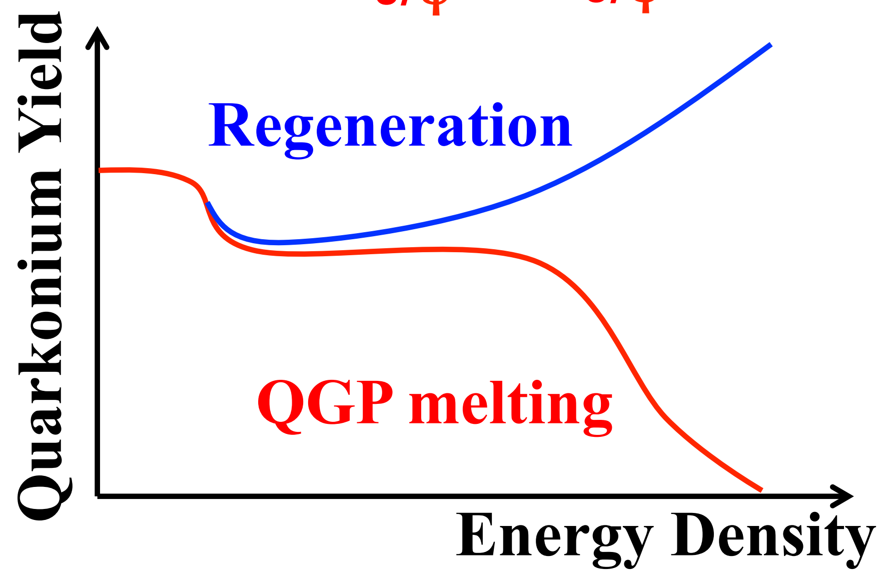


Regeneration in QGP due to quark coalescence

➔ ***Deconfinement is a prerequisite***

$\propto N_{c\bar{c}}^2$

More important at low p_T

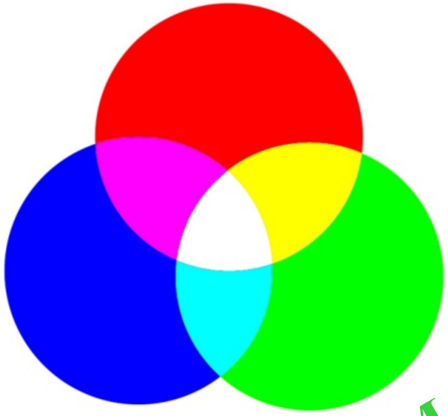


Quarkonium in heavy-ion collisions

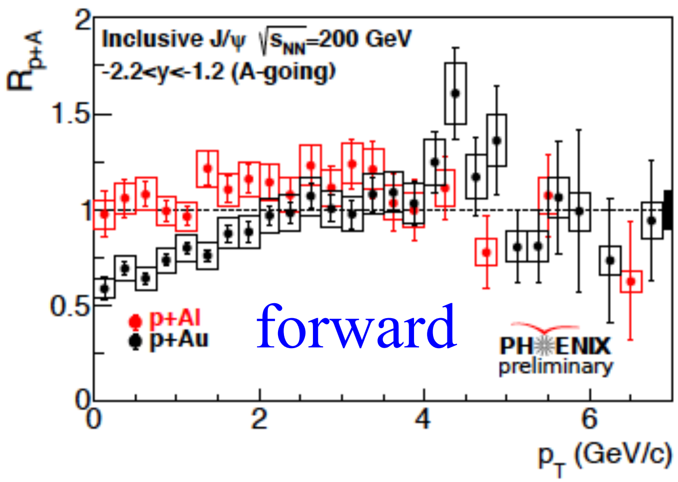
Quarkonium production also modified by cold nuclear matter (CNM) effects on top of hot matter effects

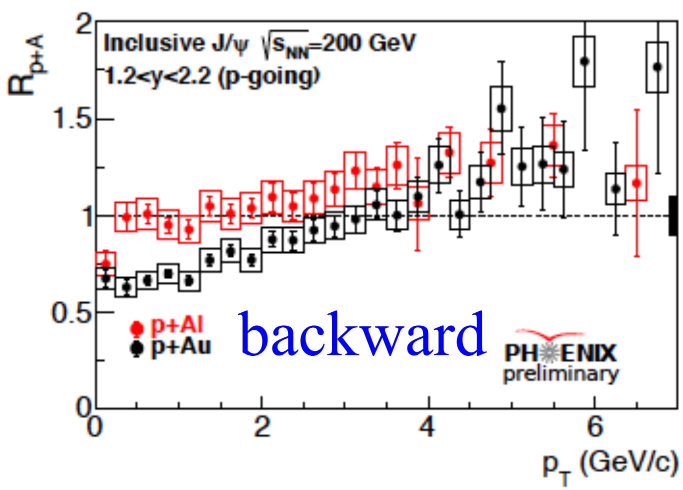
Quarkonium production in heavy-ion collisions are the interplay of color-screening/melting, regeneration and CNM effects

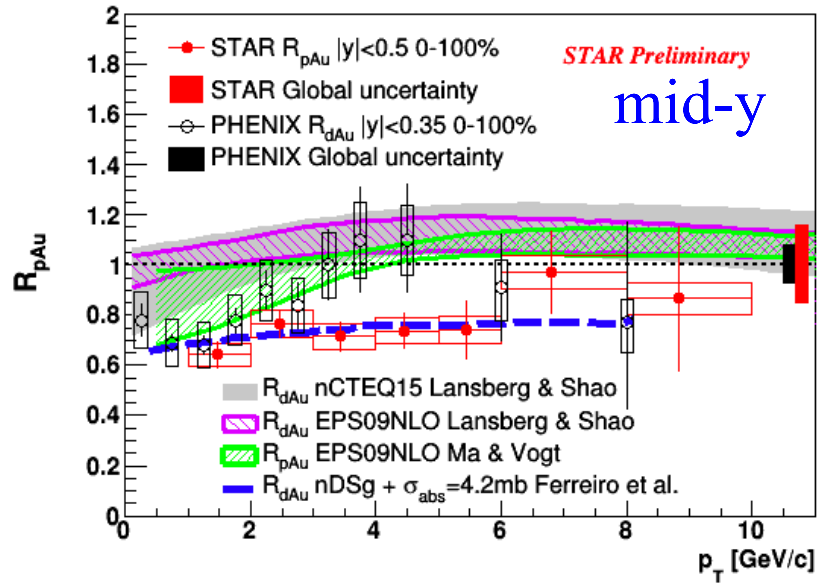
Each of the effect has different
species, p_T, rapidity,
collision centrality, energy, system …
dependence



J/ψ production in p(d)+Au @RHIC



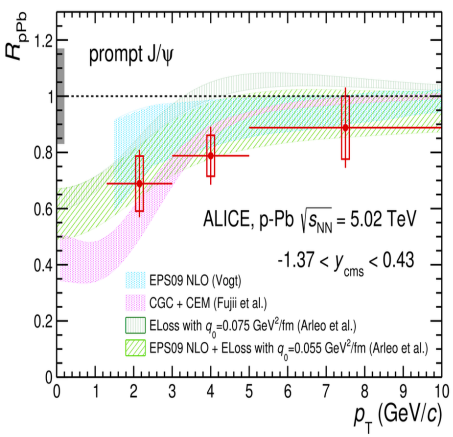




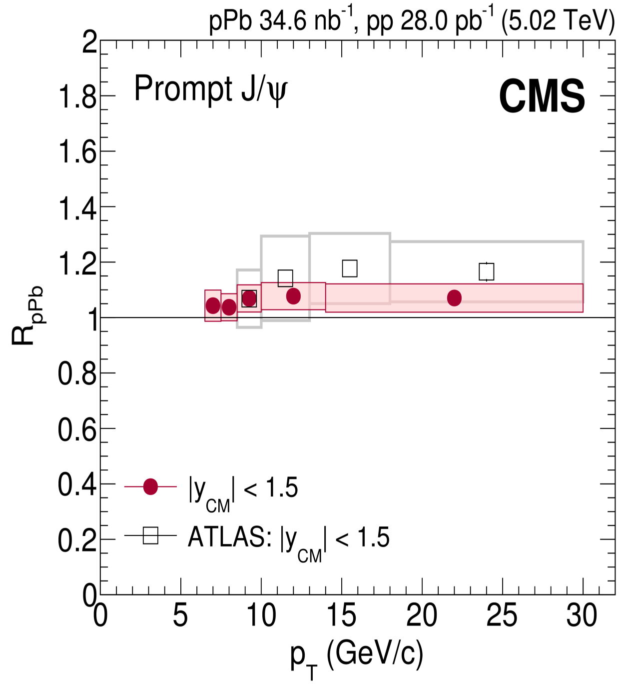
- No CNM effects observed in p+Al
- Similar increase trend in p+Au and d+Au at different rapidity
- Consistent with unity at high p_T (p_T>~ 5 GeV/c)

J/ψ production in p+Pb @LHC

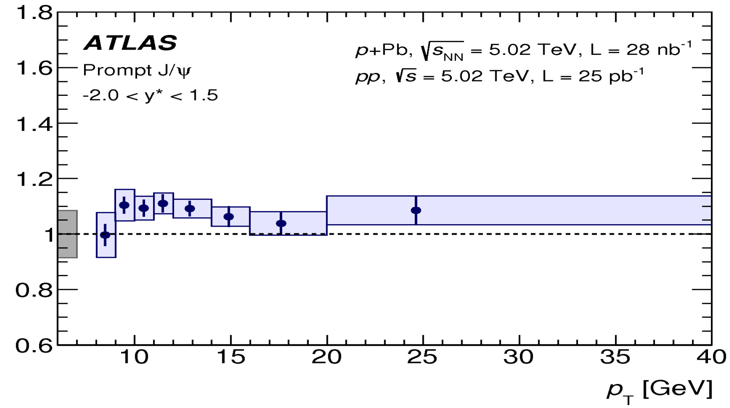
ALICE, EPJC78, 466 (2018)

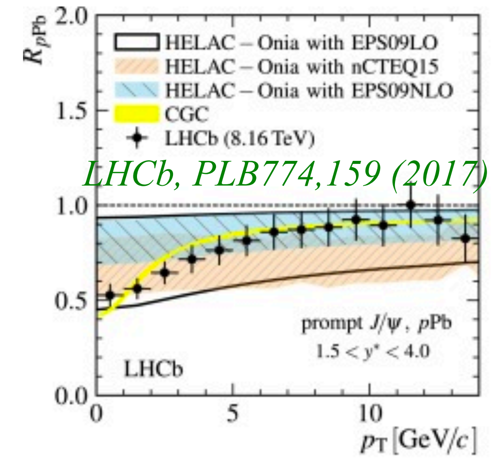


CMS, EPJC77, 369 (2017)



ATLAS, EPJC78, 171 (2018)



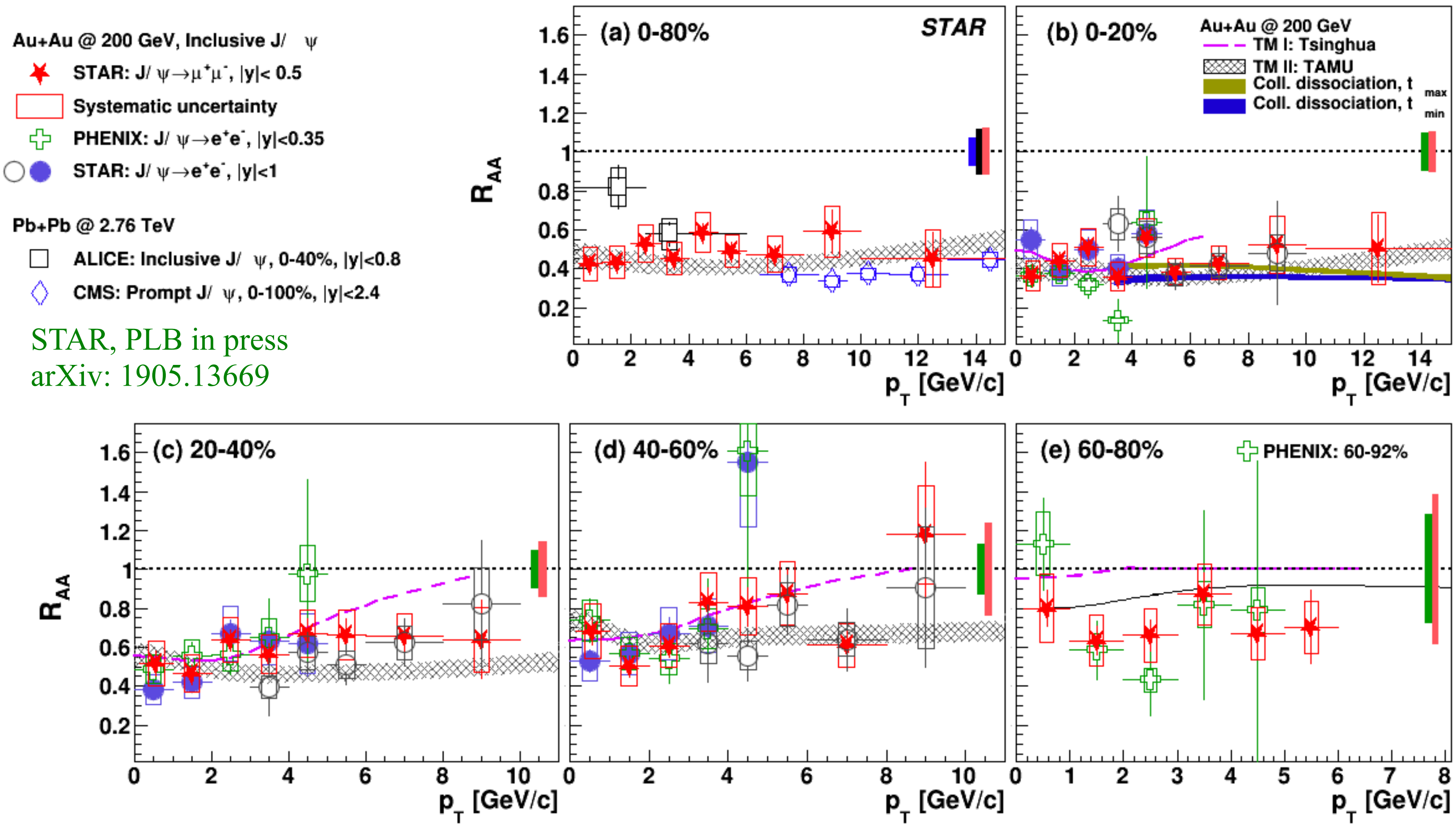


LHCb, PLB774,159 (2017)

Similar trend as at RHIC

- Low p_T: Significant suppression → CNM effects
- High p_T: Consistent with unity → CNM effects negligible

J/ψ R_{AA} vs. p_T in heavy-ion collisions



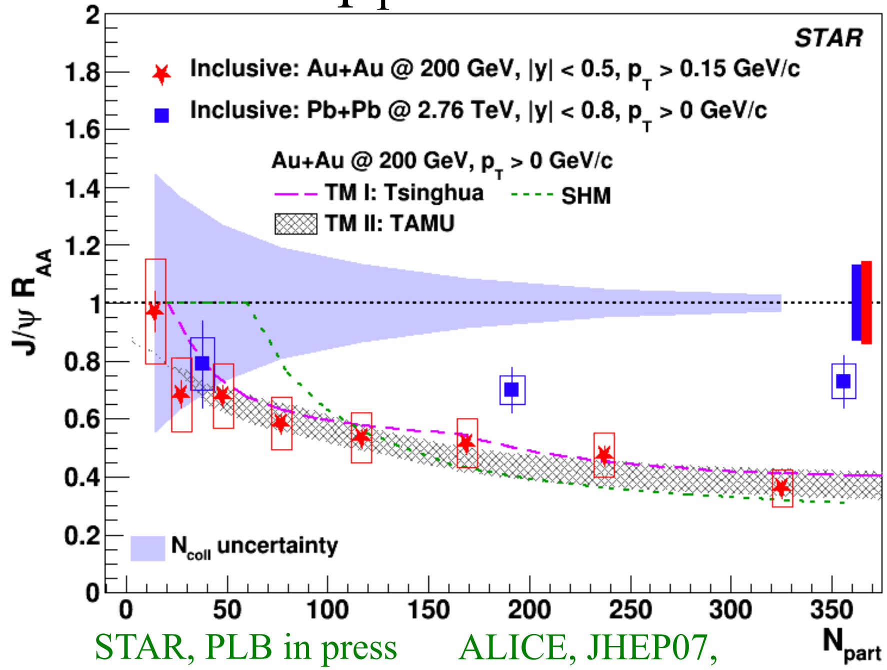
STAR, PLB in press
arXiv: 1905.13669

Data at RHIC and LHC show different p_T dependence

**All models shown include feed-down and CNM effects*

J/ψ suppression at low p_T

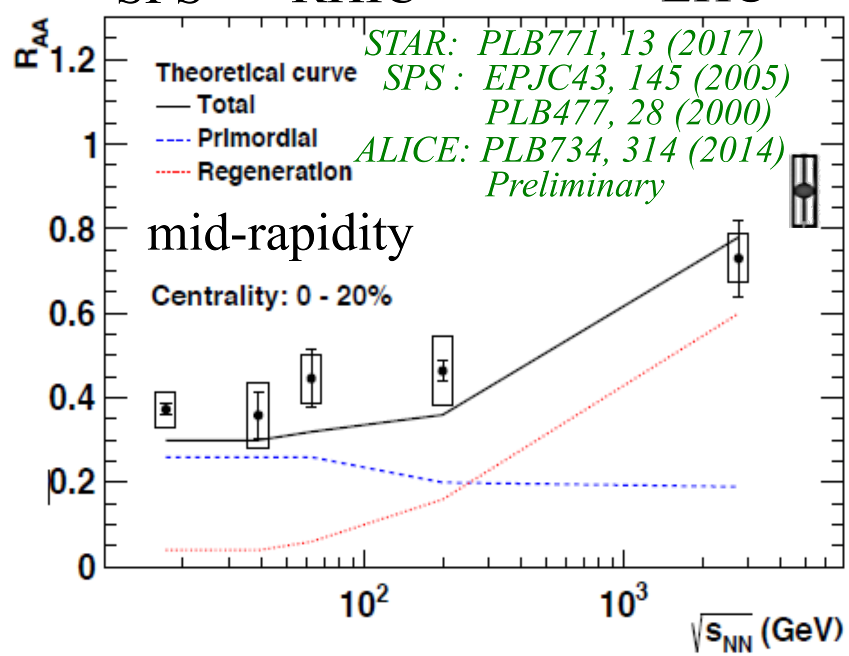
$p_T > 0.15$ GeV/c



STAR, PLB in press
arXiv: 1905.13669

ALICE, JHEP07, 051 (2015)

SPS RHIC LHC



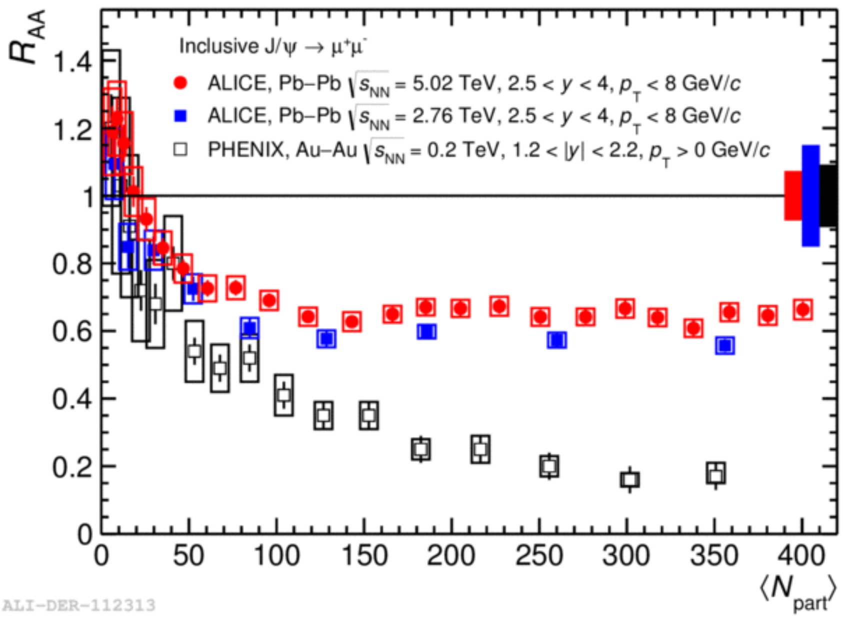
Low p_T: Interplay of melting, regeneration and CNM effects

SPS → RHIC → LHC

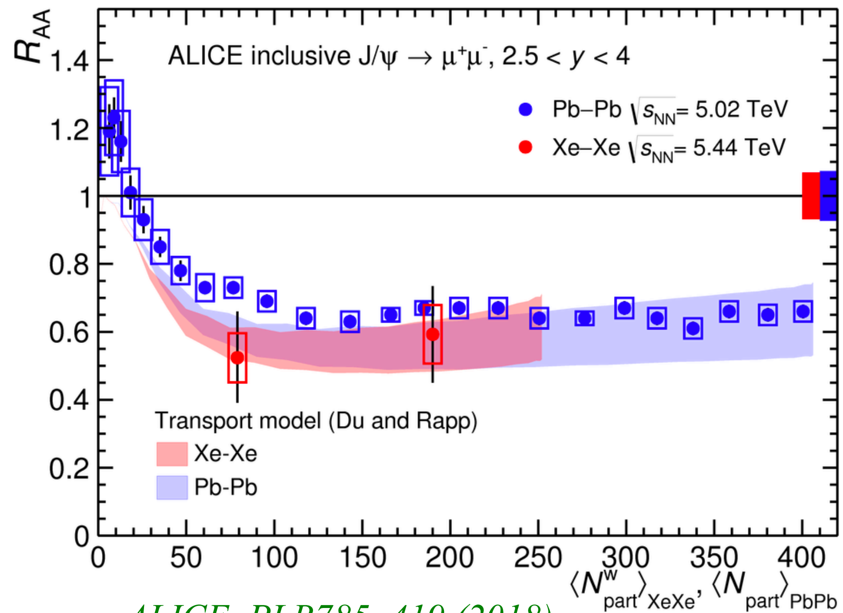
Flat or slightly increase *significantly increase*

CNM domain CNM+melting Regeneration domain

Forward rapidity



ALICE, PLB766, 212 (2017)



ALICE, PLB785, 419 (2018)

- Flat at N_{part}>100
- 2.76→5.02 TeV:
  Increase is not significant

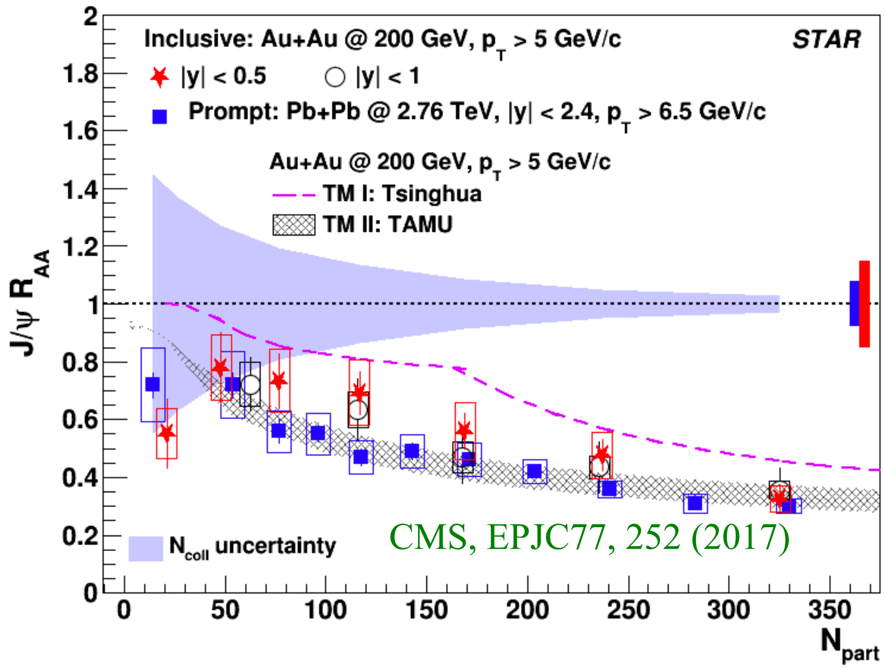
- Similar level of suppression seen in Xe+Xe and Pb+Pb

Balance of CNM, melting and regeneration

J/ψ suppression at high p_T

$p_T > 5$ GeV/c

STAR, PLB in press
arXiv: 1905.13669

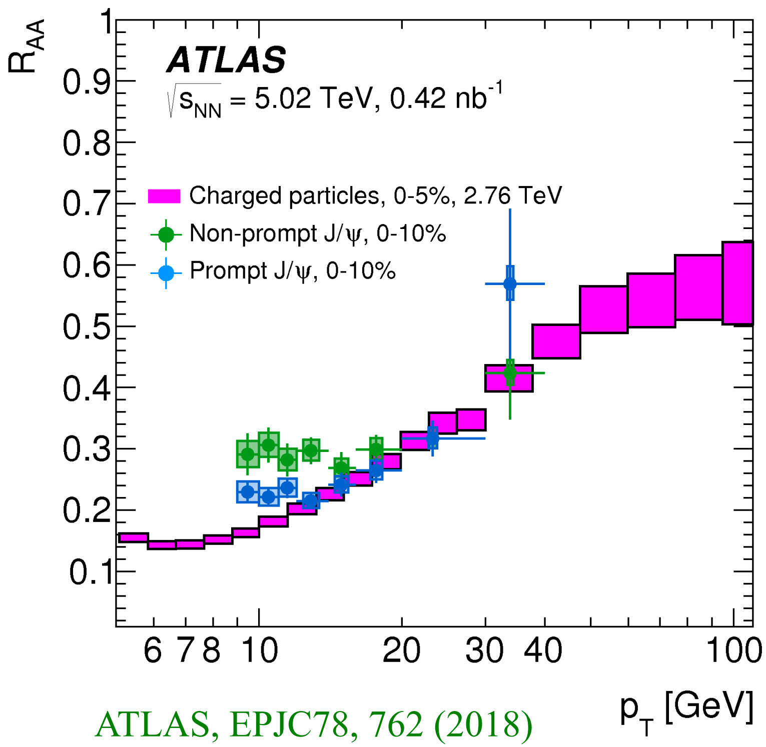


CMS, EPJC77, 252 (2017)

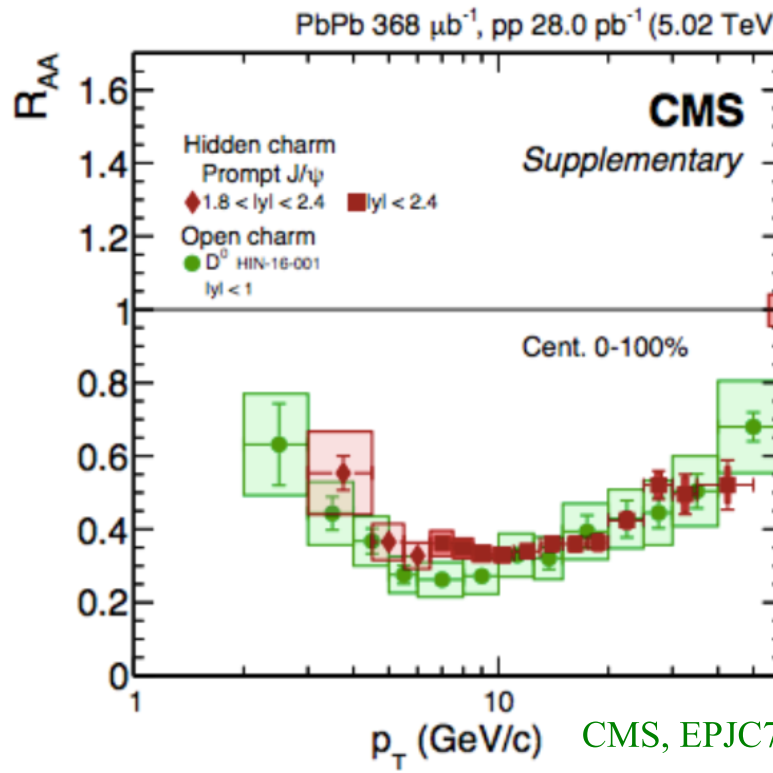
High p_T: CNM effects and regeneration are less important

- Significant suppression in central collisions → QGP melting
- Suppression systematically less at RHIC than at LHC → T at play?

J/ψ suppression at very high p_T



ATLAS, EPJC78, 762 (2018)

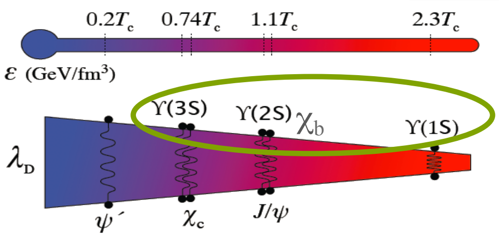


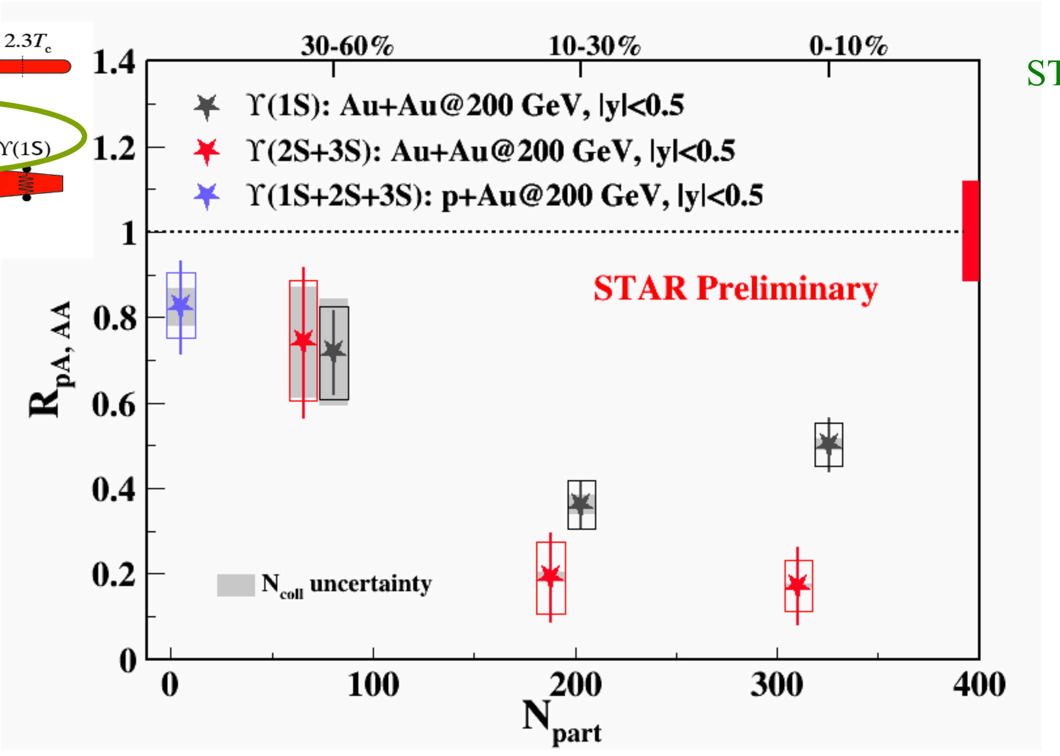
CMS, EPJC78, 509 (2018)
PLB782, 474 (2018)

J/ψ suppression at very high p_T similar as $h^{\pm}$, B→J/ψ and open charm

Driven by parton energy loss?

Upsilon suppression @RHIC



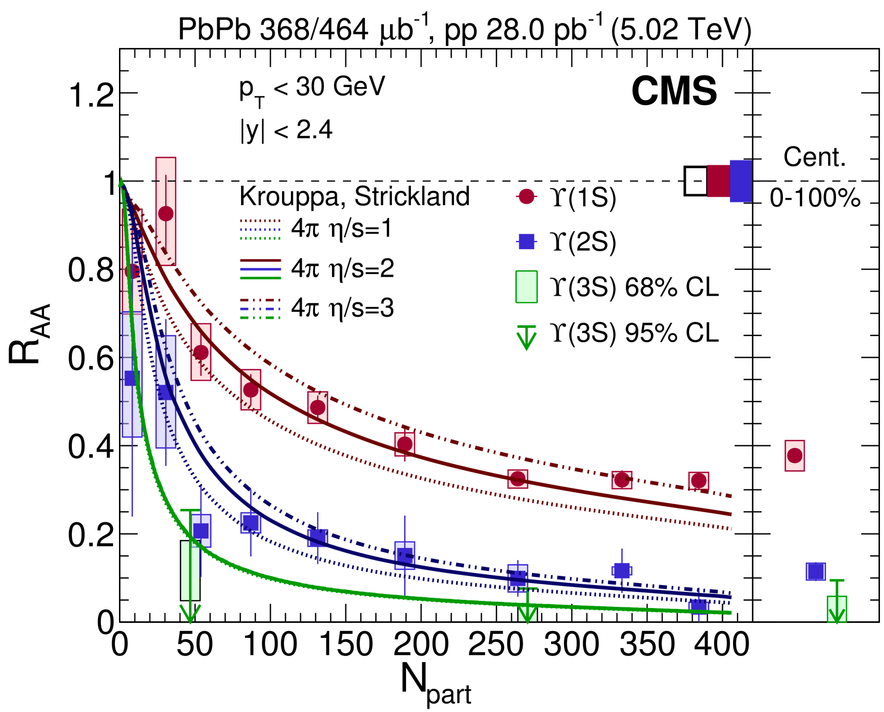


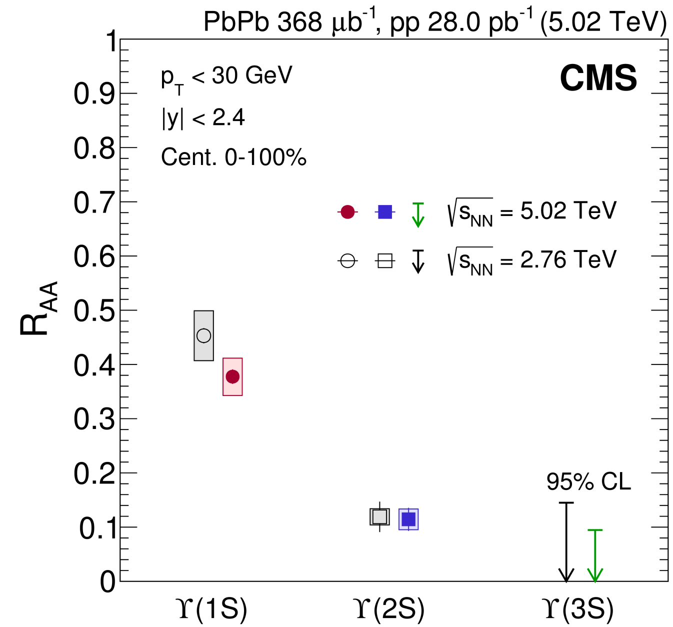
STAR Preliminary

- Most precise ϒs suppression measurements in A+A at RHIC
- More suppression in 0-30% central collisions than peripheral
- ϒ(2S+3S) more suppressed than ϒ(1S) → Sequential melting

Upsilon suppression @LHC

CMS, PLB790, 270 (2019)

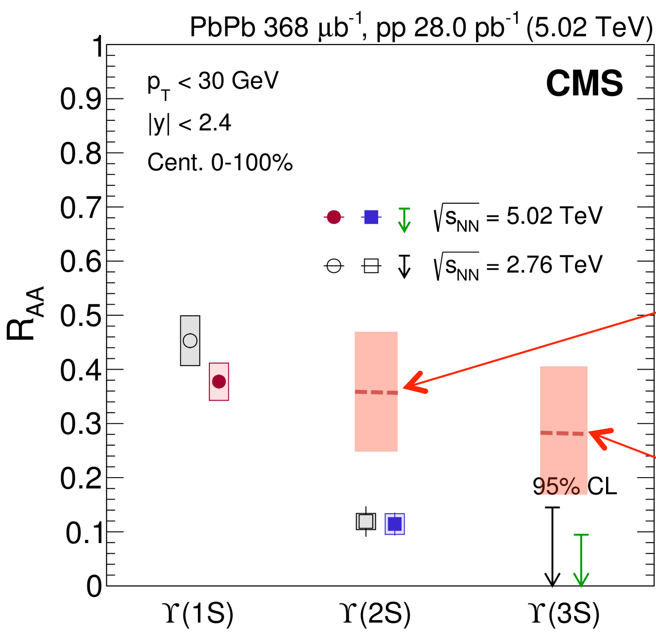




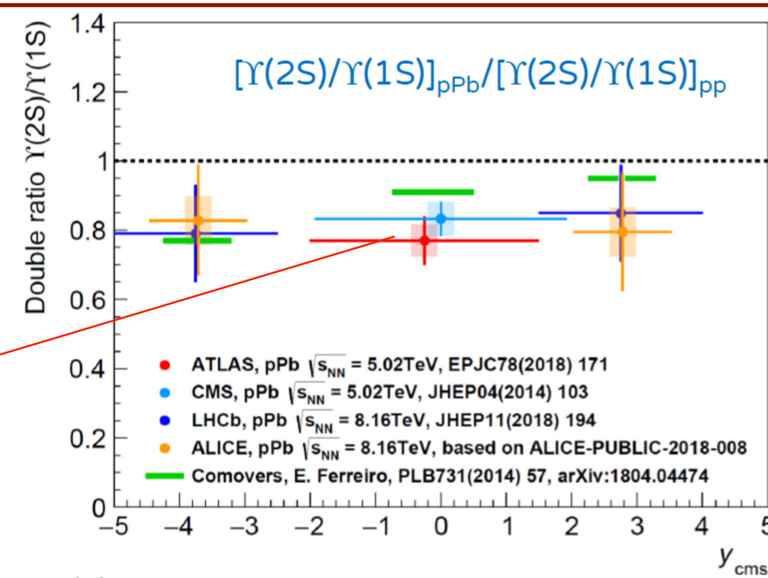
More clear signal of sequential suppression

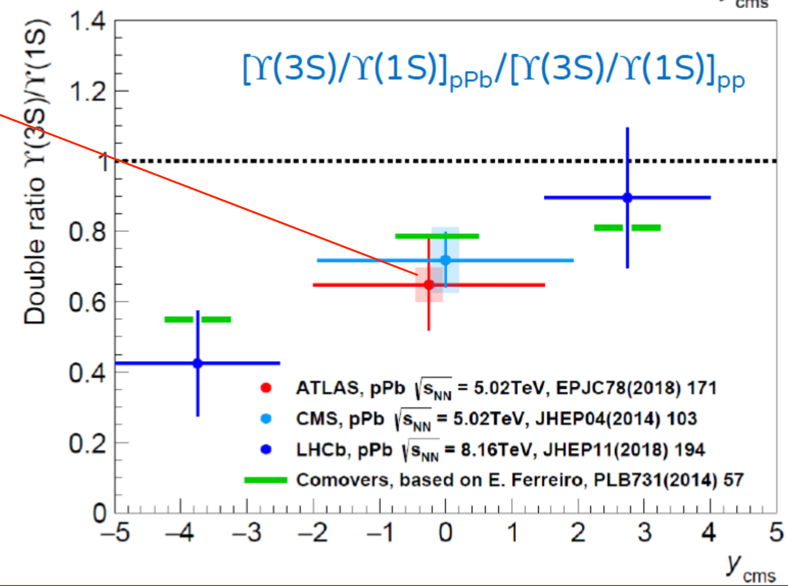
Models fairly describe the data

Can not be explained by CNM effects only



**Estimated by eyes*





Precision to be improved

Summary and Outlook

- Developments have been made to better understand the "jet quenching" mechanism
  - Isolated-photon tagged jet measurements
  - Examining flavor/mass dependent energy loss is on the way

- More/better evidences of deconfinement via quarkonia recently
  - Heavy quark coalescence (regeneration) seen in low-p_T J/ψ
  - QGP melting in high-p_T J/ψ
  - Sequential suppression in Upsilon states

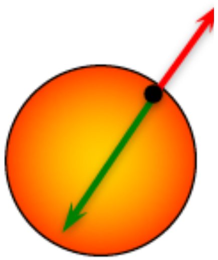
Coming in near future:

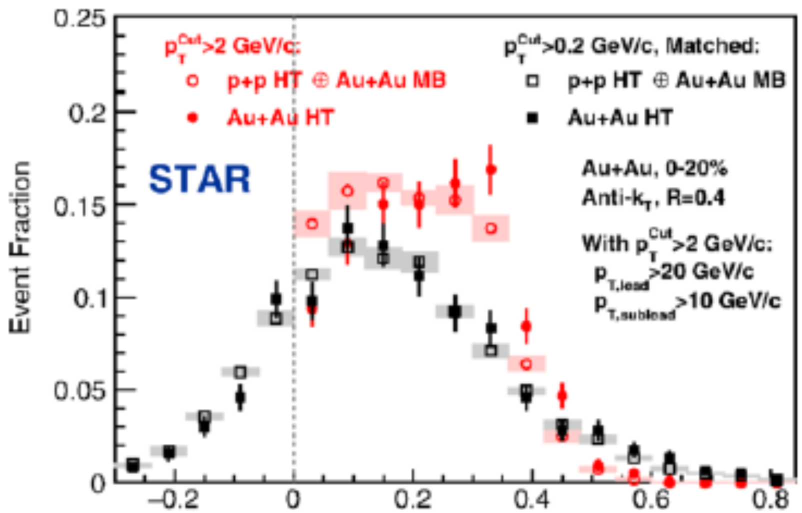
sPHENIX@RHIC and LHC Run3 data

Significantly increase the statistics (orders of magnitude)

Thanks!

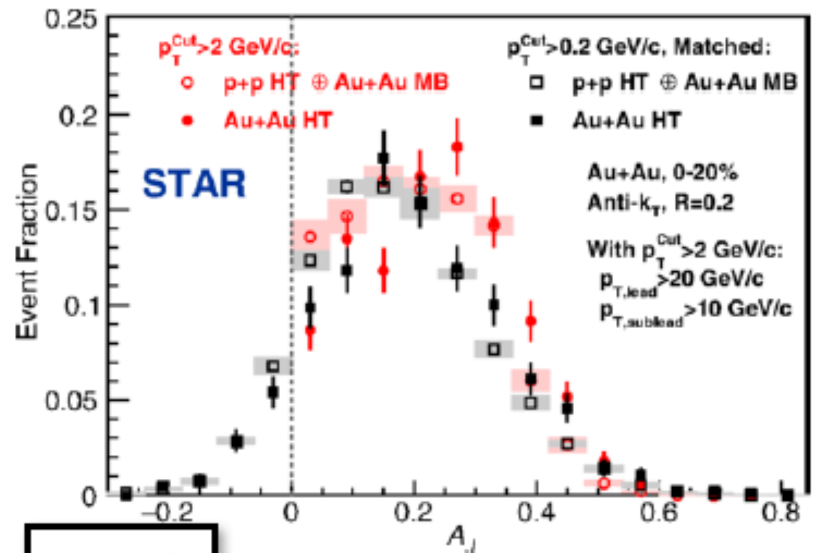
Di-jet imbalance





R=0.4

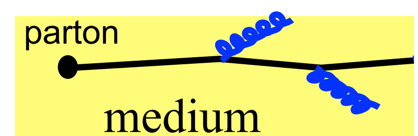
$$A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$$



R=0.2

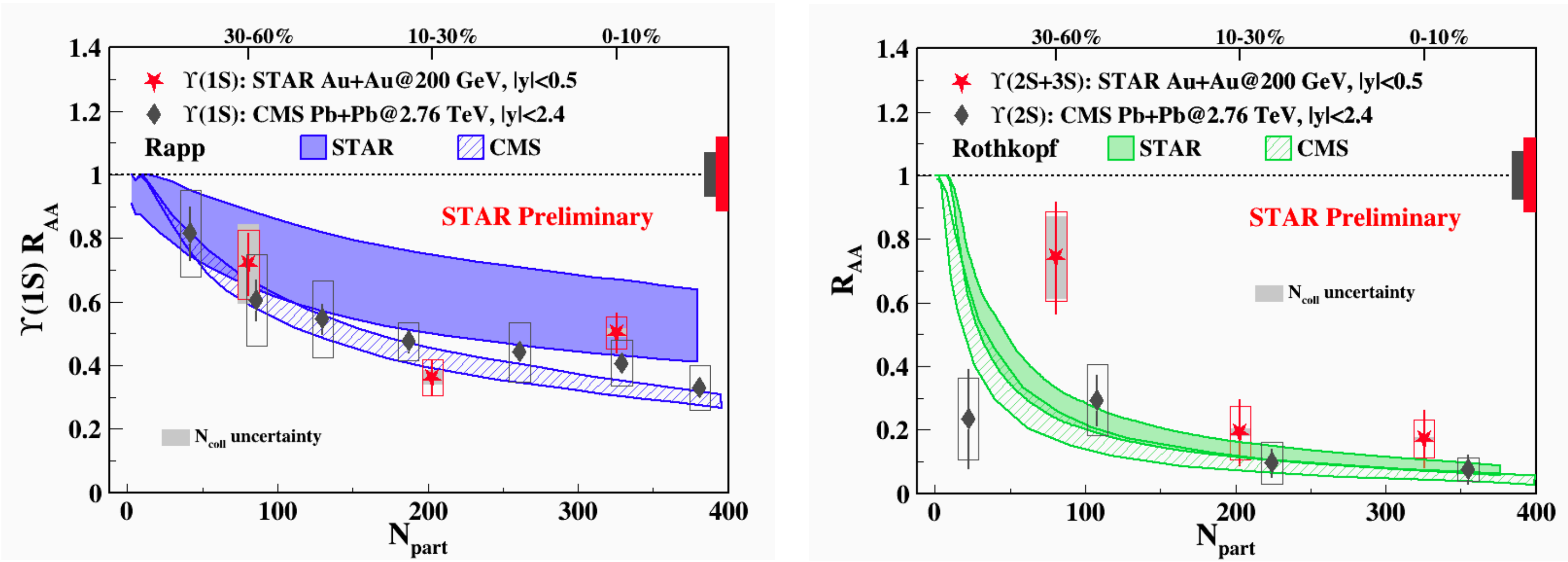
STAR, PRL119, 062301 (2017)

- For R=0.4, more di-jet imbalance in Au+Au compared to p+p
- Balance recovered when soft constituents are included
- For R=0.2, balance no longer recovered even includes soft particles



→ Softening of jet constituents and broadening of jet structure

Upsilon suppression: RHIC vs. LHC



Υ(1S): Similar suppression at RHIC and LHC, within uncertainties

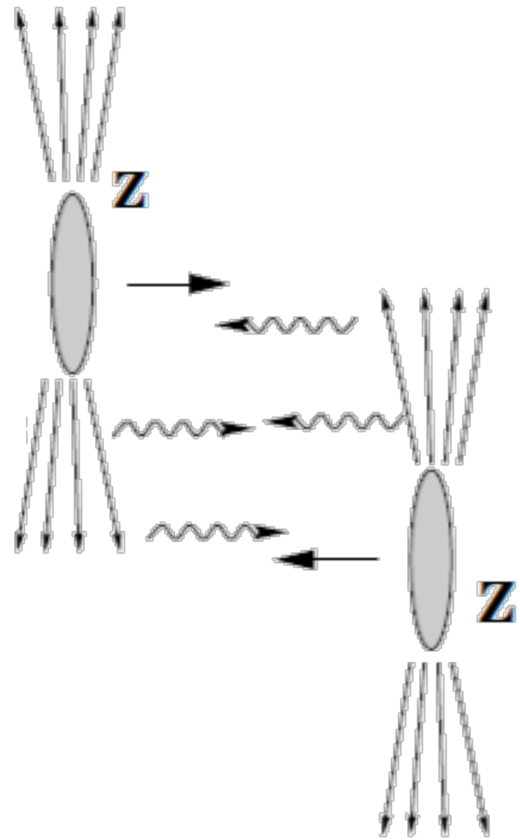
Υ(2S+3S): Systematically stronger suppression at LHC than at RHIC

Models describe the data at both energies
(tension in peripheral collisions for excited states)

Electromagnetic field in heavy-ion collisions

- Strong EM field accompanies the nuclei in relativistic heavy-ion collisions

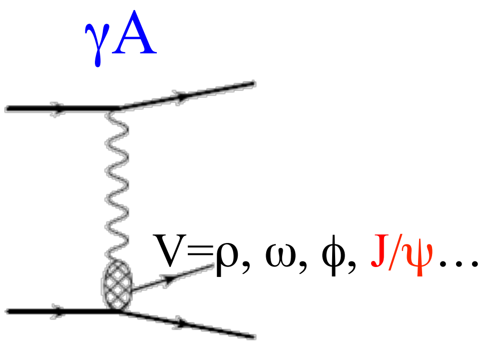
  $B \sim \gamma Zeb/R^3 \sim O(10^{14}\ Tesla)$ @RHIC

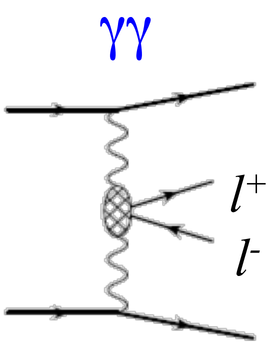


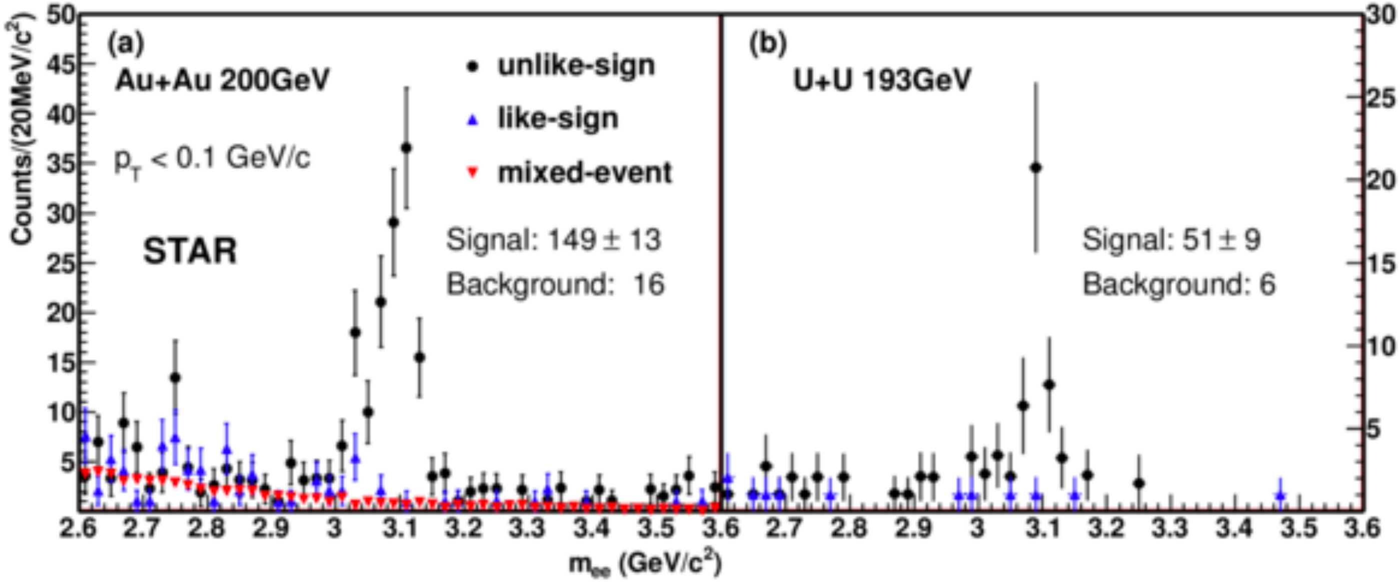
- The Lorentz contracted EM field can be expressed in terms of equivalent photon flux *E. Fermi, Z. Phys. 29, 315 (1924)*

- The quasi-real photons can initiate γA or γγ collisions in relativistic heavy-ion collisions

Clear J/ψ signals at very low p_T



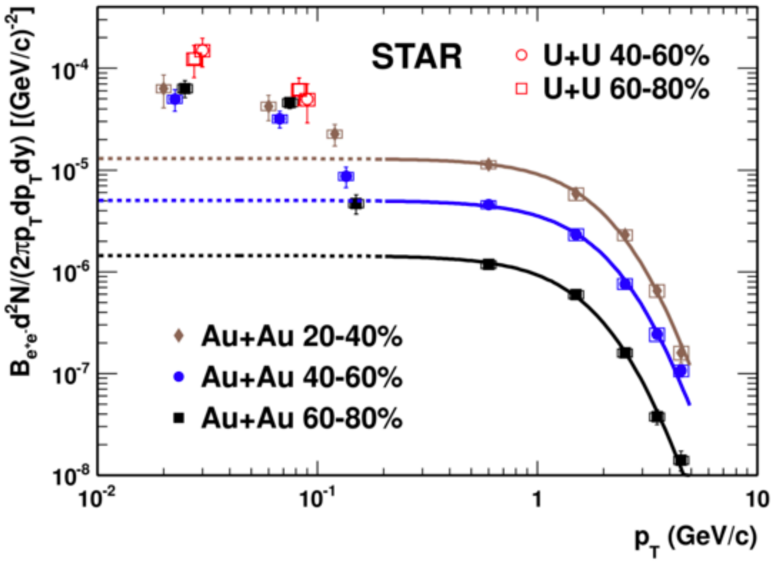


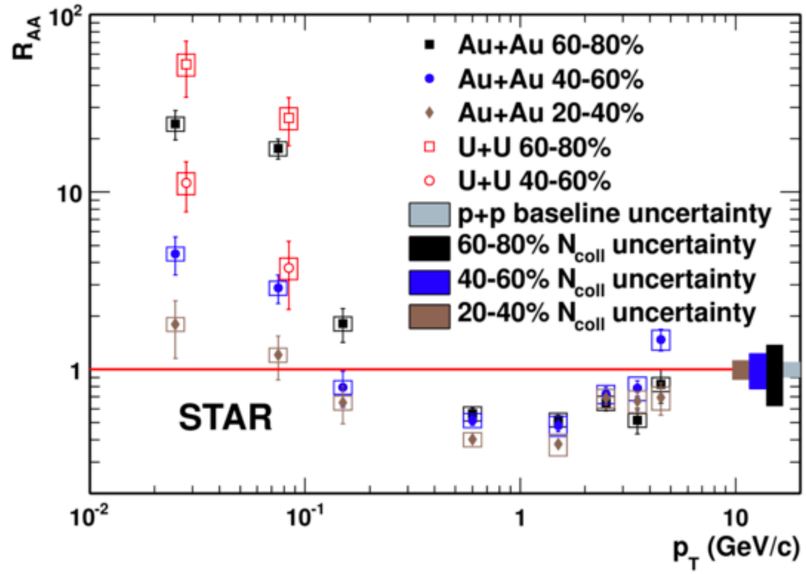


STAR, PRL121, 132301 (2018)

arXiv: 1904.11658, accepted by PRL

Very-low-p_T J/ψ enhancement at STAR



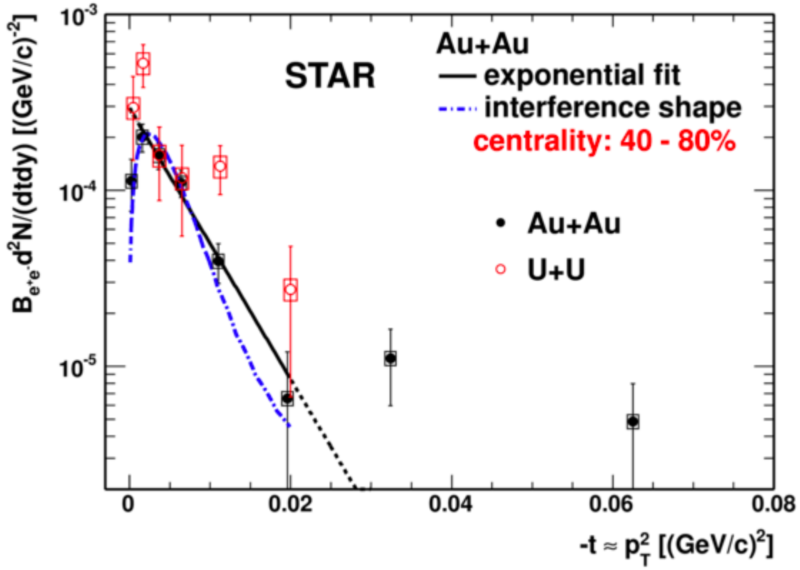


Fit fun. (empirical): $$\frac{a}{\left(1+b^2 p_T^2\right)^n}$$

Significant enhancement of J/ψ yield at p_T<0.1 GeV/c in (semi-)peripheral Au+Au and U+U collisions, R_{AA} ~ 40

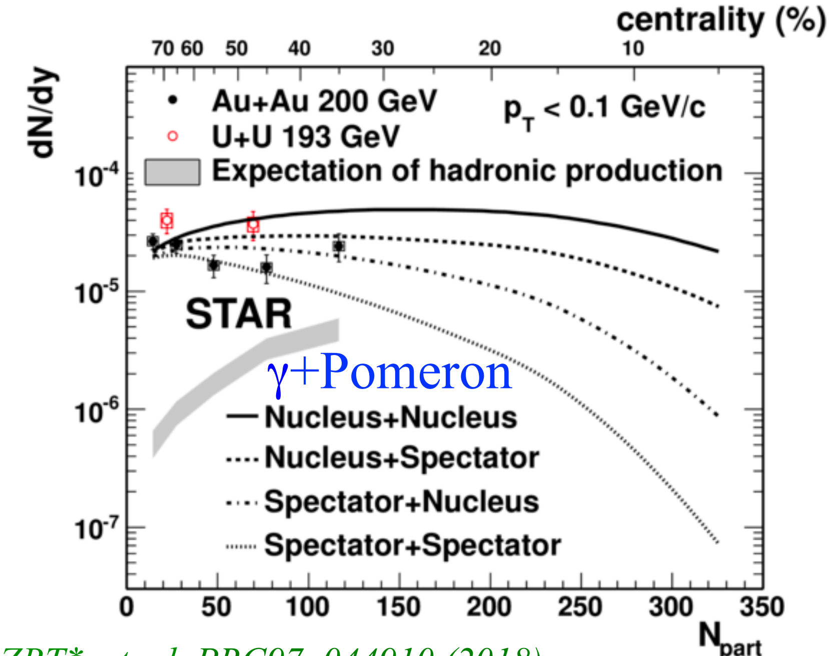
Confirm ALICE observation (PRL116, 222301 (2016))

Momentum transfer squared distribution



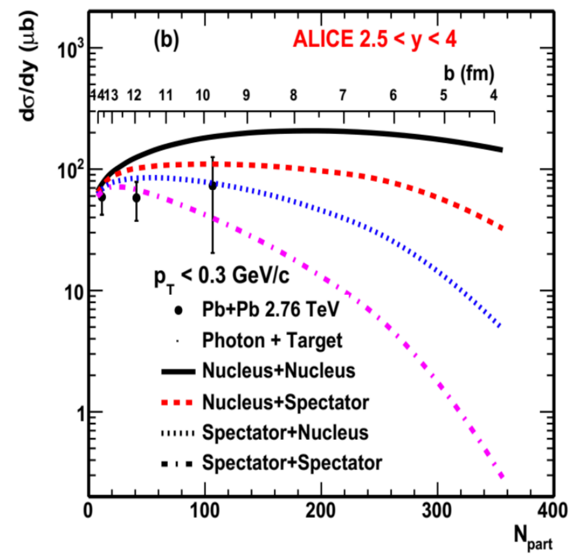
- First -t distribution of J/ψ production at low p_T in non-UPC
- Slope = 177 ± 22 (GeV/c)$^{-2}$ consistent with expected from coherent photoproduction for an Au nucleus (199 (GeV/c)$^{-2}$)
- The drop at the lowest bin may be an indication of interference χ^2/ndf = 4.8/4

Centrality dependence of yield



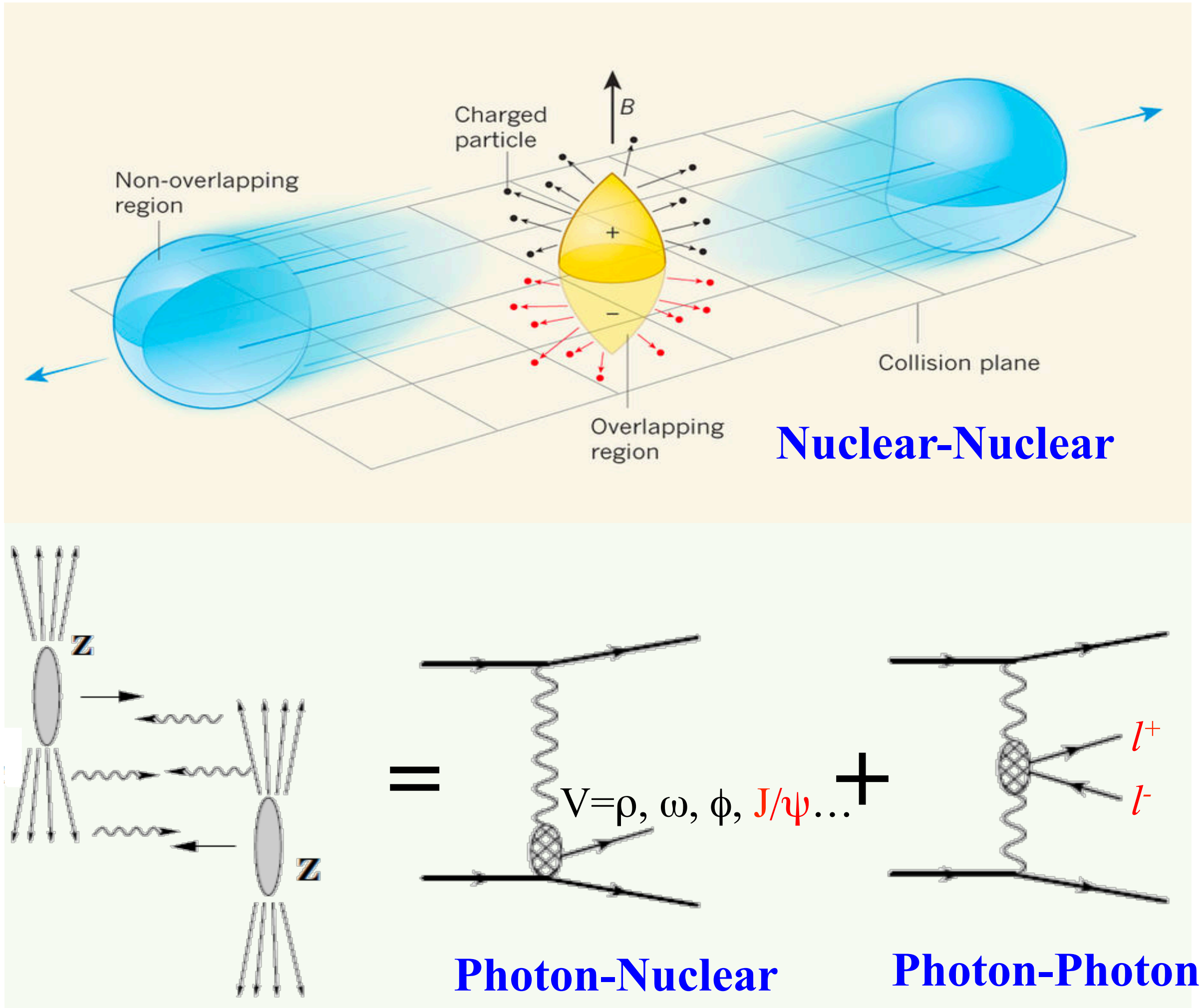
W. Zha, …, ZBT, et. al, PRC97, 044910 (2018)*
W. Zha, L. Ruan, ZBT*, Z. Xu, S. Yang, PRC99, 061901 (R) (2019)*
W. Zha, L. Ruan, ZBT*, Z. Xu, S. Yang, PLB789, 238-242 (2019)*
Z. Cao, …, W. Zha, CPC43, 064103 (2019)*

ALICE, PRL116, 222301 (2016)



- No significant centrality dependence for very-low-p_T J/ψ
- Model calculations with all scenarios describe data at b~2R
  - "Nucleus+Spectator" and "Spectator+Nucleus" are favored

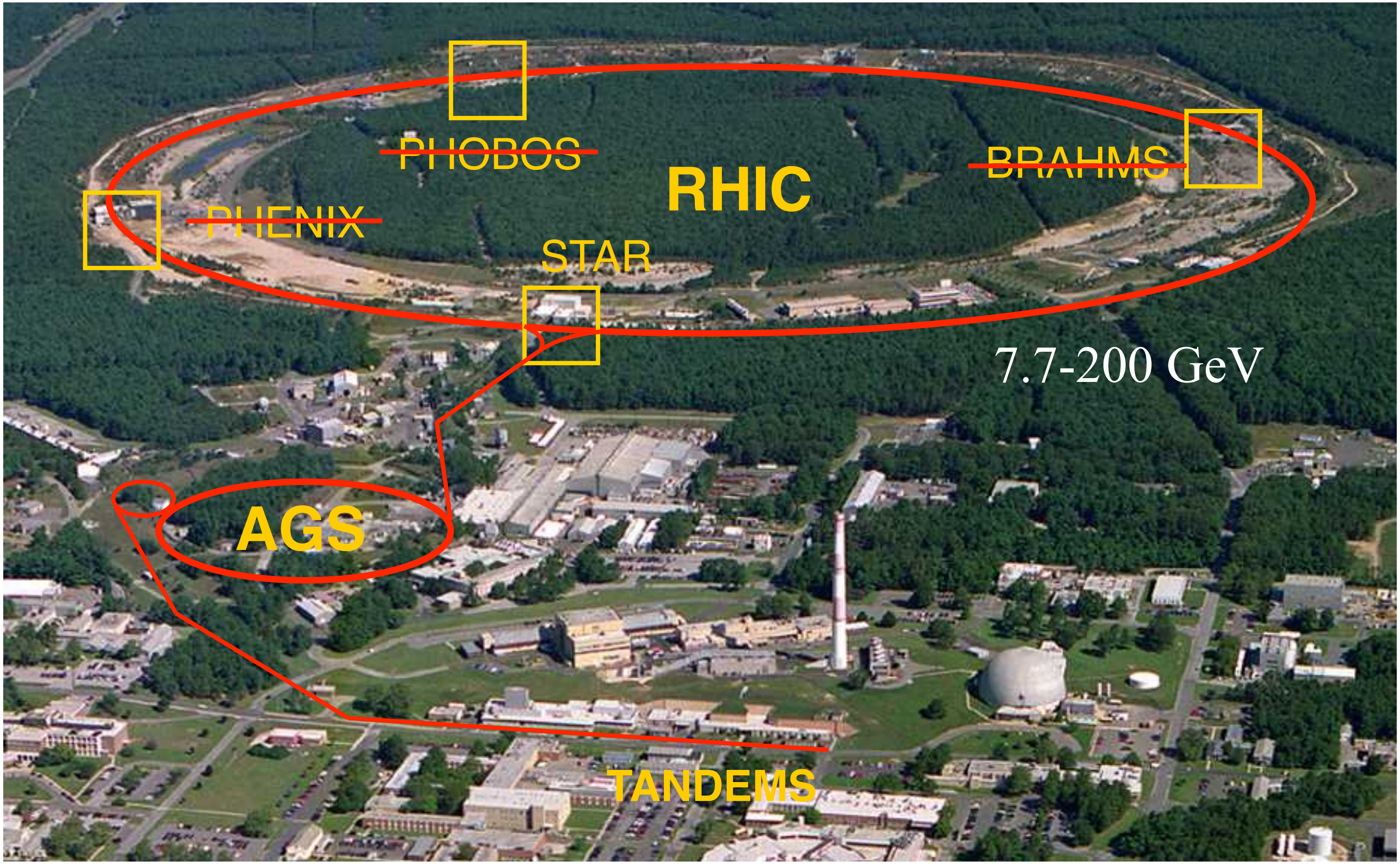
Coherent photoproducts in QGP



Novel probe of QGP

- Deconfinement
- EM field
- …

Relativistic Heavy Ion Collider @BNL



Large Hadron Collider @CERN